In compliance with the
Canadian Privacy Legislation
some supporting forms
may have been removed from
this dissertation.

While these forms may be included
in the document page count,
their removal does not represent
any loss of content from the dissertation.

C

University of Alberta

The effect of opening size on light, temperature and the growth of white spruce under a trembling aspen canopy

by

Janet Marie Pritchard ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment
of the requirements for the degree of Master of Science

In

Forest Biology and Management

Department of Renewable Resources

Edmonton, Alberta

Fall 2003

National Library
of Canada

Acquisitions and
Bibliographic Services

395 Wellington Street
Ottawa ON K1A 0N4
Canada

Bibliothèque nationale
du Canada

Acquisisitons et
services bibliographiques

395, rue Wellington
Ottawa ON K1A 0N4
Canada

Your file Votre référence
ISBN: 0-612-87863-5
Our file Notre référence
ISBN: 0-612-87863-5

The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L'auteur conserve la propriété du droit d'auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou aturement reproduits sans son autorisation.

Canada

University of Alberta

Library Release Form

Name of Author: Janet Marie Pritchard

Title of Thesis: The effect of opening size on light, temperature and the growth of white spruce under a trembling aspen canopy

Degree: Master of Science

Year this degree granted: 2003

Permission is hereby granted to the University of Alberta Library to reproduce single copies of this thesis and to lend or sell such copies for private, scholarly or scientific research purposes only.

The author reserves all other publication and other rights in association with the copyright in the thesis, and except as herein provided, neither the thesis nor any substantial portion thereof may be printed or otherwise reproduced in any material form whatever without the author's prior written permission.

July 8 03

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled The effect of opening size on light, temperature and the growth of white spruce under a trembling aspen canopy submitted by Janet Marie Pritchard in partial fulfillment of the requirements for the degree of Master of Science in Forest Biology and Management

Date July 2/03

Abstract

Reduced light levels limit growth of white spruce (*Picea glauca* (Moench) Voss) beneath trembling aspen (*Populus tremuloides* Michx.), but aspen cover provides protection from growing season radiative frosts. The creation of circular openings around individual spruce can provide more light, but reducing opening size limits the chance of radiative frost. This study examined the relationship between opening size and light and temperature levels in the center of circular gaps as well as the relationship between spruce growth and light levels in natural gaps. Results indicated a strong relationship exists between post-treatment light levels and opening size after considering pre-treatment light levels. Spruce stem volume growth was explained by light level and initial crown surface area. The relationship between opening size and temperature was weak with minimum temperatures more affected by the height and density of the surrounding stand than the actual size of the openings.

Acknowledgements

I would like to thank my supervisor Dr. Phil Comeau for his help with the set-up, implementation and writing of this thesis. Thanks also to my academic committee members Dr. V.J. Lieffers and Dr. J. Hoddinott for their suggestions during my committee meeting.

I would like to express my appreciation of a number of people who helped with the field work for this project. Thanks go to Mihai Voicu, Ryan Cheng, Sandra Babiuk, Carolyn Huston and Lynn Reich for their many hours of cutting and measuring during the summers of 2002 and 2003.

Funding for this project was provided by the National Science and Engineering Research Council of Canada and from Forest Renewal B.C. Assistance with site location in Alberta was gratefully received from Ian Whitby of Weyerhaeuser Canada and from Gary Harmata of Alberta Plywood. In B.C. Richard Kabzems from the B.C. Ministry of Forests provided assistance with site locations and also shared re-measurement data from the Siphon Creek research trials.

Throughout the pursuit of this post-graduate degree I have enjoyed the trading of ideas and encouragement received from people with whom I share my office. In particular I would like to thank Barb Logan, Anisul Islam and Dan MacIsaac. I would also like to thank Mihai Voicu and Cosmin Filipescu for all of their help with my defense preparation.

Finally, I would like to thank my husband Dave and my son Calvin for their continual support and encouragement of my going back to school to pursue this Master of Science degree.

Table of Contents

1. General Introduction and Literature Review 1
1.1 Benefits of mixtures 4
1.2 Regeneration and Development of Mixedwood Stands 7
1.3 Management challenges 11
1.4 Project focus 15
1.5 References 16
2. Effects of size of circular openings on light and temperature levels under young trembling aspen stands. 23
2.1 Introduction 23
2.2 Materials and Methods 32
2.2.1 Data Analysis 42
2.3 Results 46
2.3.1 Light transmittance at 1 m in relation to opening size and SVF 46
2.3.2 Vertical gradients of light levels 52
2.3.3 Temperature 60
2.3.4 Frequency of frost and SVF 66
2.3.5 Growing degree days 71
2.4 Discussion 73
2.5 Conclusions 80
2.6 References 81
3. The effect of light level on growth of white spruce under a trembling aspen canopy 89
3.1 Introduction 89
3.2 Materials and Methods 96
3.2.1 Data Analysis 100
3.3 Results 104
3.3.1 Growth versus DIFN and initial crown surface area 104
3.3.2 Growth versus light absorbance 111
3.4 Discussion 117
3.5 Conclusions 122
3.6 References 123
4. Implications of tending individual white spruce using radial treatments 132
4.1 Introduction 132
4.2 Effects of treatment radius on spruce growth 133
4.3 Conclusions 142
4.4 References 143

List of Tables

Table 2.1. Locations and average stand characteristics of 18 individual stands near Slave Lake, AB and near Fort St. John, B.C. 33

Table 2.2. Opening diameters (m) required in stands of differing heights (m) to achieve different values of sky view factor 34

Table 2.3. A summary of characteristics of sampled stands 47

Table 2.4. A summary of estimates of transmittance levels in relation to pre-treatment transmittance and SVF created by openings of different sizes 52

Table 2.5. Model fit and significance of individual coefficients for three multiple linear regression models describing vertical light transmittance in relation to measurement height 54

Table 2.6. Maximum proportion of available light blocked by overhead vegetation as predicted by 3 models 59

Table 2.7. Proportion of available light blocked for a relative height of 0.5 as predicted by 3 models 60

Table 2.8. Proportion of available light blocked for a relative height of 0.7 as predicted by 3 models 60

Table 2.9. Average of minimum daily temperatures for the period May 29, 2002 through September 16, 2002 at the three different probe heights for various SVFs 61

Table 2.10. Occurrences of cold temperatures varies by stand characteristics at different probe heights ... 66

Table 2.11. Relationship between standard deviation (SD) of minimum seasonal temperature and SVF ... 69

Table 2.12. Relationship between minimum July 3 temperature and surrounding stand density and height 70

Table 2.13. Changes in significance of relationship between GDD measured at 20 cm height and SVF with period of measurement 72

Table 2.14. Difference in light extinction level between sky view exposed when no opening is made and that exposed when SVF=0.5 for various positions of relative height 77

Table 3.1. Stand locations and average age, height, basal area and density of aspen in stands where white spruce were sampled near Slave Lake 97

Table 3.2. Siphon Creek research trial original densities 100

Table 3.3. Ranges of characteristics of white spruce sampled near Slave Lake 104

Table 3.4. Ranges of characteristics of white spruce sampled at Siphon Creek 104

Table 3.5. Ranges of characteristics of overstory trembling aspen 105

Table 3.6. R^2 (RMSE) values for regression models using log transformed variables 106

Table 3.7. Comparison of stem volume growth rates for white spruce with a CSA of 15,000 cm^2 at low moderate and high light levels near Siphon Creek and Slave Lake 111

Table 4.1. Table of height by breast height age and site index for trembling aspen[1] and white spruce[2] ... 135

List of Figures

Figure 2.1. General location of the selected study sites near Fort St. John, B.C. and near Slave Lake, AB. ... 32

Figure 2.2. Examples of hemispherical photographs taken in a 7.7 meter tall stand near Slave Lake before (2a) and after treatment (2b) with a small circular opening size (2.5.m radius) giving a SVF of 0.095 at ground level and 0.12 at a 1 meter measurement height. ... 35

Figure 2.3. Digital photograph of an untreated plot. In 3a the photo is automatically registered and gridded by the SLIM model, in 3b after thresholding the photo, SLIM determines what portions in the view are sky and what portions are foliage and tree stems and in 3c the solar path has been overlain and below canopy radiation is determined by using the gap fraction calculated by thresholding the photograph and estimating the penetration of direct and indirect light through the canopy ... 37

Figure 2.4. The LAI- 2000 with a 2050 optical light sensor. In 4a the basic unit and in 4b the LAI-2000 is attached to a 9 meter height pole and readings are taken every 1m above plot center to establish a vertical light profile ... 39

Figure 2.5 Relationship between growing season transmittance measured with hemispherical photographs and the SLIM program and DIFN values calculated from measurements taken with LAI-2000. The dashed line show a 1:1 relationship and the solid line can be described by the equation: growing season transmittance = 0.09331+ 0.8748*DIFN; R^2=0.905. The intercept is significantly greater than 0 ($p<0.0001$) and the slope is significantly different than 1 ($p<0.0001$). ... 40

Figure 2.6. Scatterplot of residuals and studentized residual (corrected by standard error) values and predicted values of post-treatment transmittance as produced from the relationships given by the model LnPst-treatment transmittance = LnSVF + LnPre-treatment transmittance for each of the three separate models as represented in figures 2.8-2.10. ... 43

Figure 2.7. Scatterplot of studentized residual values and predicted values of post-treatment extinction as produced from the relationships given by the model LnPost treatment Extinction = LnRelativeHeight + LnSVF for Slave Lake stand heights 2-3.3 m (2.7a); Slave Lake stand heights 3.5-8 m (2.7b); and Fort St. John 3.5-8m (2.7c) as described in Table 2.5 on page 53 ... 45

Figure 2.8. Scatterplot showing relationship between post treatment transmittance and sky view factor (SVF) and pre treatment transmittance for Slave Lake plots only. The lines are described by the equation: Ln(post-trt transmittance) = 0.23607 + 0.294046 Ln (SVF) + 0.254233 Ln (pre-trt transmittance); R^2 = 0.8231, RMSE = 0.206, n=54. ... 48

Figure 2.9. Scatterplot showing relationship between post treatment transmittance and sky view factor (SVF) and pre treatment transmittance for Ft. St. John plots only. The lines are described by the equation: Ln(post-trt transmittance) = 0.245799 + 0.169665 Ln (SVF) + 0.428911 Ln (pre-trt transmittance); R^2 = 0.7168, RMSE = 0.241, n=54. ... 50

Figure 2.10. Scatterplot showing relationship between post treatment transmittance and sky view factor (SVF) and pre treatment transmittance for Slave Lake & Ft. St. John plots. The lines are described by the equation: Ln(post-trt transmittance) = 0.299779 + 0.231178 Ln (SVF) + 0.381009 Ln (pre-trt transmittance); R^2 = 0.7354, RMSE = 0.241, n=108. ... 51

Figure 2.11. Scatterplot showing relationship between post treatment light extinction (1-transmittance) and SVF at successive 1m heights from ground level and relative height (measurement position with respect to the average height of surrounding stand) for Slave Lake 2- 3.3 m stands. The lines are described by the equation: Ln(post-trt extinction) = -1.4883 - 0.2135*Ln(RelHt) - 0.2040* Ln(SVF); R^2 = 0.7441, RMSE = 0.219, n=54. ... 56

Figure 2.12. Scatterplot showing relationship between post treatment light extinction (1-transmittance) and SVF at successive 1m heights from ground level and relative height (measurement position with respect to the average height of surrounding stand) for Slave Lake 3.5 - 8 m stands. The lines are described by the equation: Ln(post-trt extinction) = -1.6739 - 0.2741*Ln(RelHt) - 0.2084*Ln(SVF); R^2= 0.6054, RMSE = 0.327, n=204. 57

Figure 2.13. Scatterplot showing relationship between post treatment light extinction (1-transmittance) and SVF at successive 1m heights from ground level and relative height (measurement position with respect to the average height of surrounding stand) for Fort St. John 3.5 - 8 m stands. The lines are described by the equation: Ln(post-trt extinction) = -3.1114 -1.1148*Ln(RelHt) - 0.2805* Ln(SVF); R^2= 0.6155, RMSE = 0.703, n=204. 58

Figure 2.14 2.14a– 2.14h are examples of minimum daily temperature trends for temperature probes located at 15 cm below ground (n=13), 20 cm above ground (n=12) and 1 meter above ground level (n=12) for the period July 1 – 7, 2002. Probes that had more than 5% of total seasonal readings missing were not used in the analysis. 62

Figure 2.14 (continued) 2.14i – 2.14n are examples of minimum daily temperature trends for temperature probes located at 15 cm below ground (n=13), 20 cm above ground (n=12) and 1 meter above ground level (n=12) for the period July 1 – 7, 2002. Probes that had more than 5% of total seasonal readings missing were not used in the analysis. 63

Figure 2.15. Relationship between the minimum daily temperature on July 1 -3, 2002 and SVF for the 1 meter above ground temperature probe as described by the following equations: July 1 min. temp = 7.233 – 2.36 *SVF; R^2=0.367; p=0.037; n=12, July 2 min. temp = 3.08 – 3.39 *SVF; R^2=0.400; p=0.027; n=12, and July 3 min. temp = -1.36 – 4.09 *SVF; R^2=0.373; p=0.035; n=12. 65

Figure 2.16. Relationship between the number of times that the min. hourly temperature was less than –2 ° C during the period May 29 – Sept. 16, 2002 and SVF (for the 1 m above ground temperature probe) as described by the equation: # of Occurrences < –2 ° C = 7.28 + 63.08*SVF; R^2 = 0.218; p=0.126; n=12. 67

Figure 2.17. Relationship between the number of times that the min. hourly temperature was less than –2 ° C during the period May 29 – Sept. 16, 2002 and density of the surrounding stand (for the 1 m above ground temperature probe) as described by the equation: # of Occurrences < –2 ° C = 105.79 – 0.0031*density; R^2= 0.586; p=0.004; n=12. 67

Figure 2.18. Relationship between the number of times that the min. hourly temperature was less than –2 ° C during the period May 29 – Sept. 16, 2002 and the surrounding stand height (for the 1 m above ground temperature probe) as described by the equation: # of Occurrences < –2 ° C = 75.74 – 12.91*stand ht; R^2= 0.381; p=0.033; n=12. 68

Figure 2.19. Scatterplot showing relationship between the number of times that the minimum hourly was less than -2° C during the period May 29 – Sept. 16, 2002 and and density of the surrounding stand and height of the surrounding stand at 1 m above ground. The lines are described by the equation: # of Occurrences < -2 °C = 127.82 – 9.62*Standht - 0.00265*Density; R_2 = 0.7853, RMSE = 17.28, n=12. 68

Figure 2.20. Relationship between the standard deviation of the seasonal minimum temperature and SVF for the 1 meter above ground probe as described by the equation: SD of min seasonal temp = 7.11 + 1.78 *SVF; R^2= 0.45; p=0.018; n=12. 69

Figure 2.21. Scatterplot showing relationship between minimum temperature on a cold day in the growing season (July 3, 2002) and density of the surrounding stand and height of the surrounding stand) at 20cm above ground. The lines are described by the equation: Min. temperature (July 3) = -8.263 + 0.5008*Standht + 0.000126*Density; R^2 = 0.7856, RMSE = 0.892, n=12. 70

Figure 2.22. Scatterplot showing the relationship between the number of GDD accumulated prior to June 16, 2002 and SVF for temperature probes located at 20 above ground level in the stands near Slave Lake as described by the equation: accum GDD May 29 to June16 = 258.91 + 31.212*SVF; R^2=0.541, p=0.006, n=12. 71

Figure 2.23. Scatterplot showing the relationship between the min. temperature on a cold day in the growing season (July 3, 2002) and density of the surrounding stand for Slave Lake at a probe height of 15 cm below ground as described by the equation: Min temp (July 3) = 3.485 + 0.0000915*density; R^2=0.45; p=0.0073; n=13 73

Figure 2.24. Comparison between post-treatment transmittance values predicted by the model described in Figure 2.10 holding the pre-treatment transmittance value constant at 0.18 (Groot et al. (1997) intact forest transmittance level) and transmittance levels measured by Groot et al. (1997). For SVF=0.43 the Groot et al. (1997) value is for a 18 m E-W strip not a circular opening. 75

Figure 3.1. Scatterplot of studentized residual values and predicted values of periodic stem volume growth as produced from the relationship given by the model Lngrowth = Ln(CSA00) + Ln (DIFN02) for white spruce near Slave Lake 101

Figure 3.2. Scatterplot of studentized residual values and predicted values of periodic stem volume growth as produced from the relationship given by the model Lngrowth = Ln(CSA99) + Ln (DIFN01) for white spruce near Siphon Creek 101

Figure 3.3. Studentized residual plots of various models using logarithmically transformed variables as produced by the relationships given by the models in figures 3.5 to 3.9. 103

Figure 3.4. Scatterplot showing relationship between periodic growth and crown surface area in 2000 and transmittance (DIFN) in 2002. The lines are described by the equation: Ln(stemvol growth) =-5.191304 +1.041593* Ln (CSA00) + 0.463972* Ln (DIFN02); R^2 = 0.8144, RMSE = 0.539, n=45. 108

Figure 3.5. Scatterplot showing relationship between periodic growth and crown surface area in 1999 and transmittance (DIFN) in 2001. The lines are described by the equation: Ln(stemvol growth) =-8.424382 +1.457476* Ln (CSA99) + 0.648499* Ln (DIFN01); R^2= 0.8658, RMSE = 0.424, n=71. 110

Figure 3.6. Scatterplot showing the relationship between tree leaf area (LA) and crown surface area (CSA). The line is described by the equation: Ln(LA)= -13.141 + 1.272 * Ln(CSA); R^2=0.857; RMSE=0.356; n=20. 111

Figure 3.7 (a-b). Scatterplots showing the relationship between tree absorbance in the open and tree leaf area (a) or crown surface area (b). The lines describe the equations: a) Ln(Tree Absorbance)= -0.392442 + 0.146351 * Ln(LA); R^2= 0.4619; RMSE=0.1489; n=20 and b) Ln(Tree Absorbance)= -2.1374 + 0.166125 * Ln(CSA); R^2= 0.3156; RMSE=0.168; n=20 113

Figure 3.8 (a-c). Scatterplots showing the relationship between stem volume, height and root collar diameter average annual growth and canopy absorbance. The lines are represented by the equations: a) Ln(Vol)= 4.985818 + 0.4817 *Ln(CanAbs); R^2=0.1371; RMSE= 0.906, n=20; b) LnHt= 2.899725 + 0.365489 * Ln(CanAbs); R^2=0.4152; RMSE =0.324; n=20; and c) Ln(Rcdgrowth)=0.6629 + 0.299 * Ln(CanAbs); R^2= 0.3275; RMSE=0.322; n=20. For equation (a), canopy absorbance is not a significant variable (Prob |T| = 0.1080). 114

Figure 3.9. Scatterplot showing the relationship between stem volume growth and initial volume. The line is represented by the equation: Ln(Vol growth)=1.606897 + 0.912813*Ln(Initial volume); R^2=0.9026; RMSE=0.3045; n=20. 115

Figure 3.10. Scatterplot showing the relationship between average annual stem volume growth and the absorbance of a tree in the canopy and tree volume at the beginning of the measurement period. The lines are described by the equation: Ln(Vol growth)= 2.347 + 0.282*Ln(CanAbs) + 0.878*Ln(Init.vol); R^2=0.948; RMSE=0.229; n=20. 116

Figure 3.11. Scatterplot showing the relationship between average annual stem volume growth and transmittance at the tree crown and tree volume at the beginning of the measurement period. The lines are described by the equation: Ln(Vol growth)= 2.042 + 0.259*Ln(DIFN) + 0.911*Ln(Init.vol); R^2=0.940; RMSE=0.246; n=20. 117

Figure 4.1. Representation of how SVF at the top of the spruce will change over time using expected height growth trends from SITE-Tools (SI50 of 17m for spruce and 21m for aspen). D=opening diameter in meters. 135

Figure 4.2. Change in transmittance values over time based on expected height growth of aspen and spruce growing within various sized openings utilizing changing SVF at the top of the spruce over time (Figure 4.1) and the vertical light profile relationship described in equation 2. D=opening diameter. 136

Figure 4.3. Change in transmittance values over time based on expected height growth of aspen and spruce growing within various sized openings utilizing changing SVF at the top of the spruce over time (Figure 4.1) and the vertical light profile relationship described in equation 3. D=opening diameter. 137

Figure 4.4. Stem volume growth as predicted from equation 4 for white spruce near Slave Lake for trees with initial CSA of 5,000 and 10,000 cm^2 under pre-treatment light levels of 0.2. 140

Figure 4.5. Stem volume growth as predicted from equation 4 for white spruce near Slave Lake for trees with initial CSA of 30,000 and 75,000 cm^2 under pre-treatment ligh[illegible]els of 0.2. 141

1. General Introduction and Literature Review

Upland mesic sites of the mixedwood section of the western boreal forest are dominated by mixtures of trembling aspen (*Populus tremuloides* Michx.) and white spruce (*Picea glauca* (Moench) Voss) (Rowe 1972; Beckingham and Archibald 1996) with variable amounts of balsam poplar (*Populus balsamifera* L.), white birch (*Betula papyrifera* Marsh.), black spruce (*Picea mariana* (Mill.) B.S.P.) and balsam fir (*Abies balsamea* (L.) Mill.) (Thorpe 1992).

In the western Canadian provinces in the first half of the twentieth century, mixedwood stands were basically exploited to remove the large white spruce (Lieffers and Beck 1994; Andison and Kimmins 1999). This was followed by a period of trying to convert mixedwood stands to more desirable softwood stands (Lieffers and Beck 1994). A conversion that was often ineffective with competition from grasses and trembling aspen making this strategy expensive (Smith et al. 1997) and often unsuccessful (Lieffers and Beck 1994). Successful establishment of spruce dominated stands immediately following harvesting of mixedwood stands can be achieved through site preparation and stand tending activities provided that effective treatments are used, and that treatments are applied at ideal times. This requires a commitment to undertake all necessary tending, in an appropriate sequence, and at appropriate times, as well as substantial investment. Also starting in the late 1970s, technological developments and expanding markets began making hardwood species more desirable (MacDonald 1996; David et al. 2001) and brought an increased public concern about widespread conversion of mixedwood stands to stands of pure softwoods (Andison and Kimmins 1999).

The overlapping of hardwood and softwood tenures in Alberta makes management of a mixedwood system challenging. Practicing understory spruce protection (to protect a species that will ultimately benefit another company) means higher costs for hardwood producers (Lieffers and Beck 1994). Site preparation and stand tending to control aspen establishment and dominance in areas considered as softwood producing may mean hardwood producers are not meeting their own production objectives.

To predict how a given stand will develop with time, we must understand stand dynamics, or the study of changes in forest stand structure with time, including stand behaviour during and after stand disturbances (Oliver and Larson 1996). Forest level management plans establish overall management objectives for a specific stand type such as mixedwood stands. If the overall goal is to promote the growth of white spruce while at the same time maintain the trembling aspen component, then a silvicultural system that will help to meet that objective must be chosen. Silviculture is the manipulation of forest stands to meet a given management objective and is the ultimate application of stand dynamics knowledge (Oliver and Larson 1996). A silvicultural system includes all of the management activities that will take place within a given stand throughout the entire length of the rotation including harvesting, regeneration and stand tending.

The natural long delay in the development of white spruce in mixedwood stands can be decreased by seedling development in the understory of the previous stand (Lieffers and Beck 1994). Some of the ways to manage mixedwoods would include: careful logging of aspen to protect understory spruce in mixedwood stands (MacDonald 1996; Greene et al. 1999; David et al. 2001); and the active encouragement of white spruce in the understory [examples include: underplanting (Navratil 1996) and management of seed sources and seedbeds via activities such as timing of harvest (Greene et al. 1999) and spot scarification (Stewart et al. 2000)]. Use of shelterwood, group selection or individual tree selection systems, can also lead to a head start for young spruce in mixedwood stands. Other systems that could be utilized include: clearcut with seed trees or, strip cuts (Navratil 1996). In many of these partial cut systems it is important to consider the wind firmness of the trees that remain after each cutting stage (Navratil 1996).

The two-stage harvesting – stand tending model proposed by Brace and Bella (1988) is another method to promote growth of white spruce in mixedwood stands and it also takes into account the wind firmness of any leave trees. This method proposes a first harvest when the aspen overstory is 60-80 years old and the white spruce is 20-60 years old. In this initial cut all of the aspen is removed as well as the large spruce that if left would be susceptible to wind damage. Aspen will re-sprout in the openings created and at this time fill planting with spruce in areas of inadequate spruce stocking could also be done. Sixty years later both aspen and spruce are harvested.

Strip cuts of varying size and orientation or small openings of varying shapes (Carlson and Groot 1997) have also been proposed to allow establishment of more shade tolerant species in the openings. The size and orientation of openings must be appropriate to provide enough light for vigourous spruce growth while at the same time being small enough to provide some of the protective benefits of a nurse crop. The use of these types of silvicultural systems as opposed to a clearcut system can be more expensive because of the increased harvesting and road building costs (Lieffers and Beck 1994) but these costs can be somewhat offset by decreased white spruce establishment costs and stand tending costs.

1.1 Benefits of mixtures

Recently there has been an increasing interest in the benefits of maintaining these mixedwood stands for biodiversity, promoting long term soil and site productivity and reducing risk of frost and insect damage (Comeau et al. 1996). Deciduous based forest tenure holders have developed an increased desire to improve growth of white spruce in stands that have traditionally been managed for hardwood production. They are seeing the value of management techniques that will encourage growth of white spruce while at the same time ensure continued aspen growth. (Mann and Lieffers 1999). In order to improve growth of white spruce, management techniques need to be designed to balance some of the conflicting requirements for optimum growth and survival of the two species. One of these conflicts results when opening a stand to promote white spruce growth (by increasing light levels) can lead to increased radiative frost damage of the white spruce which are easily damaged when grown in open conditions (Groot et al. 1997).

There is some debate over the question of whether mixed stands are more productive than monocultures. Day and Bell (1988) argue that pure stands of white spruce are more productive while others (Man and Lieffers 1999; Kelty et al. 1992) argue that mixtures are more productive. Mixed stands of white spruce and trembling aspen tend to develop a stratified canopy even when the two species considered individually are much the same age. Shade tolerance can be defined as the physiological and morphological characteristics that may confer greater or lesser capacity to grow in the shaded understory (Messier et al. 1999). Aspen, which is considered very shade intolerant (Daniels et al. 1979) or shade intolerant (Lamontagne 1998; Beaudry et al. 1999) grows aggressively while young and white spruce, which is generally considered moderately shade tolerant (Thorpe 1992; Beaudry et al. 1999) has slower juvenile growth and is able to survive in more shaded environments. Combinations of shade tolerant and shade intolerant species often work well to take advantage of a given set of resources.

One of the reasons why these two species develop and grow well together may be because as a mixture they make more complete use of available light by increasing the total light interception by the stand (Kelty et al. 1992). This is because the lower canopy positions of the aspen are unable to survive at lower light levels and do not effectively absorb light at much depth in the canopy but these light levels are sufficient for shade tolerant white spruce to grow. Spruce absorbs this light and is able to capture light that would be otherwise unutilized in a pure aspen stand. This stratified canopy structure also ensures that the total light use efficiency is greater because shade adapted white spruce uses light more efficiently at low light levels (Kelty et al. 1992).

In addition to the benefits that can be attributed to more complete and efficient use of available light in stratified canopy stands, there are also morphological adaptations that help the individual species survive and thrive in mixedwood associations. In low light conditions, white spruce is able to adapt a more horizontal spread of its tree crown to capture more of the limited light resources (Oliver and Larson 1996; Chen 1997). Specific leaf area (SLA) measured as cm^2 of leaf area/g of leaf, is higher in leaves developed in low light because individual needles are usually thinner and broader than needles developed in high light environments (Awada and Redmann 2000; Chen 1997; Messier et al. 1999; Aphalo and Ballaré 1995; Duchesneau 2000). Leaves developed in shaded environments are adapted to concentrate the reduced amounts of incoming light on as small a volume of tissues as possible. In low light, it is most important to maintain a positive photosynthetic/respiration balance (Sprugel et al. 1996). Thicker needles would have higher construction and maintenance costs but would not increase photosynthetic activity because light is so limiting. To experience increased productivity, the individual species in mixedwood stands must use the available site resources differently and ultimately more completely and not simply subdivide the total resource base that one highly efficient species may be able to use completely on its own (Kelty et al. 1992; Kimmins 1997).

Spruce/aspen species mixtures are also potentially more productive in that there can be reductions in crown competition (Man and Lieffers 1999), improved litter decomposition and nutrient cycling (Man and Lieffers 1999), nurse tree benefits (Kelty et al. 1992, Man and Lieffers 1999), pest attack reduction (Kelty et al. 1992; Man and Lieffers 1999) and compensatory growth in that when one species succumbs to a given stress related factor, the other species may survive and respond with increased growth (Kelty et al. 1992).

The situation can arise where one species directly benefits from the presence of another (Kelty et al. 1992) such as nitrogen fixing red alder growing with Douglas-fir (Binkley et al. 1992) or the potential of trembling aspen to protect the more frost sensitive white spruce from summer frost damage (Groot and Carlson 1996).

The economic consequences of alternative management strategies must also be considered. Because in the past, hardwoods were not considered as desirable as conifers, mixedwood stands may have been bypassed (MacDonald 1996). Some sites are now available close to mills and because of this proximity; enhanced management (Alberta Environmental Protection 1998) of these sites becomes more economically feasible. If more emphasis can be placed on maintaining these sites as truly mixedwood sites by actively promoting white spruce establishment and vigour, then social as well as biological and economic objectives can be realized. A challenge is finding cost-effective ways to tend mixedwood stands to achieve different objectives. The costs of establishing and maintaining pure spruce plantations can be substantial and savings can be realized by allowing a more natural progression of stand development and then applying stand tending practices to promote the growth and vigour of white spruce. Practicing the natural disturbance approach to management in western boreal forests has become more common as is satisfies a more holistic management objective.

1.2 Regeneration and Development of Mixedwood Stands

Most mature mixedwood stands originated following fire (Lieffers and Beck 1994) but mixedwood stands can also originate following harvesting, windstorm damage and defoliation damage. Fires of low to moderate intensity leave some surface organic matter which is favourable to aspen (Thorpe 1992) as it invades freshly disturbed sites easily from root suckers and even to some extent from wind borne seeds when the timing of the seed bed and seed sources coincides (Andison and Kimmins 1999). Hot fires expose mineral soil, which is more favourable to conifer establishment (Thorpe 1992) particularly if there is a nearby source of available seed.

Mixedwood stands also develop following harvesting with a similar range of species mixtures becoming established. In the absence of planting, development of aspen dominated stands is likely to be favoured in large clearcuts because of a lack of nearby available spruce seed. Partial cuts, strip cuts and small clearcuts are more favourable to spruce establishment particularly where there is a nearby seed source.

Trembling aspen tends to be the dominant species early in the life of a mixedwood stand. Aspen tends to regenerate vigorously following a disturbance (David et al. 2001) and can be classified as a pioneer species with its early rapid growth and general dominance of young mixedwood stands (Peterson and Peterson 1995). The ability of aspen to regenerate via vegetative means gives it a large advantage over white spruce in areas where the disturbance is large (Greene et al. 1999). Mineral soil exposure is not required for the establishment of trembling aspen as most of their reproduction is through vegetative suckering following a disturbance (David et al. 2001). High light levels stimulate root suckering and ensure vigourous growth of aspen (Haeussler et al. 1990). Trembling aspen prefer sites that have a mesic moisture regime and a moderate nutrient regime (Beckingham and Archibald 1996).

White spruce are generally present to a greater or lesser extent in these same site types (Thorpe 1992; Beckingham and Archibald 1996) as they also prefer mesic, moderate nutrient areas for establishment. A good mineral seedbed or humus exposed by disturbance is required for the establishment of white spruce (Thorpe 1992) but natural regeneration of white spruce is unreliable (Greene et al. 1999). This is especially the case where the disturbance covers a large area, as seed dispersal is generally low into areas greater than 100 meters from the edge of a cutover or area burned by wildfire (Dobbs 1976) and seed masting is marked and unpredictable (Greene et al. 1999). The proper degree of disturbance which will expose mineral soil or humus is also often lacking. The proportion of spruce in the originating stand is often low, limiting the total amount of available seed (Greene et al. 1999). Most white spruce stems establish in the first few years following a disturbance (Thorpe 1992) but the actual period of recruitment can be quite variable (Oliver and Larson 1996).

White spruce tends to establish and grow slowly under the aspen canopy (Messier et al. 1999). Spruce can survive and grow adequately under aspen canopies, except when aspen are very dense, since aspen canopies usually allow an adequate amount of light to penetrate to lower canopy locations (MacDonald 1996). Light levels under aspen canopies are generally related to basal area of young aspen, which is the product of diameter and density of the aspen (Comeau 2001, Pinno et al. 2001, Lieffers et al. 2002). Also, there are periods within a given year, particularly during spring, when white spruce gets the advantage of more open growing conditions before aspen leaf-out (Constabel and

Lieffers 1996). With its slow juvenile growth, white spruce (Thorpe 1992) is able to survive for a long period of time in an understory position (Thorpe 1992; Greene et al. 1999). This persistence allows spruce to take advantage of gaps that develop in the canopy due to aspen mortality (Kobe and Coates 1997).

A young aspen-dominated mixedwood stand typically goes through a period of substantial self-thinning in its first 10 years of life. Within the first 20 years, aspen densities can go from 30,000 stems per hectare or higher, to less than 15,000 stems per hectare (Bella 1986). This is caused primarily by competition amongst the aspen for available light (Andison and Kimmins 1999), for water, and the effects of pathogens. The ability to naturally self-thin confers an advantage (Peterson and Peterson 1995) to the aspen as it can vigourously invade and take over a site and at the same time, naturally form straight, branch-free boles in trees that will ultimately become the leading ones (Smith et al. 1997).

The leaf area of a young mixedwood stand, which is comprised mostly of aspen stems, increases up to age 15 to 25 years typically when light levels become very low and stands go through a 'competition bottleneck' (Lieffers et al. 2002). At this point the aspen begins to break up and go through self-thinning with light levels gradually increasing again as the stand ages (Geiger 1965; Lieffers et al. 2002). This self-thinning opens up the aspen canopy and gaps develop. This can provide improved growing conditions for spruce that are already established and additional white spruce can become established provided that a seed source is available and suitable seedbed conditions exist (Stewart et al. 1998).

Although aspen behaves as a pioneer, it has a short life span (Oliver and Larson 1996) with many stems dying young as a result of competition. Height growth slows down with age and stems becoming suppressed by other species such as white spruce that overtake the aspen (Smith et al. 1997). This leads to a stand that is comprised of a combination of trembling aspen and white spruce, with minor amounts of other species, that may provide some potential benefits over a single species stand.

1.3 Management challenges

Competition from aspen and balsam poplar is considered one of the major limitations to the development of coniferous species in regenerating mixedwood stands (MacIsaac and Navratil 1996). If white spruce is present in the stand following disturbance as a result of natural or artificial regeneration, its growth will not be optimized when aspen is competing with it for available light. Much of the growth suppression of the white spruce comes from inadequate light levels. Maximum photosynthesis of white spruce shoots occurs between 40% and 60% of full sunlight (Coates and Burton 1999; Spittlehouse and Stathers 1990) but there is evidence that maximum diameter and stem volume growth occurs at 100% full sunlight (Comeau et al. 1993; Coates and Burton 1999).

Because of the high latitudes of the boreal forests of Western Canada, solar elevations are relatively low even during summer. This means that many small gaps in the forest canopy never receive direct solar radiation. Light can be divided into direct and diffuse components. Direct light is that which travels directly to a given point in the tree canopy without much modification by particles in the atmosphere or by anything else blocking its path (Lieffers et al. 1999). Diffuse light (or sky light) is made up of light that has been scattered or reflected by particles within the atmosphere or by anything else that might have been in its' direct path (Lieffers et al. 1999). Diffuse light levels are much more consistent seasonally and daily than direct light levels because of the constantly changing path of the sun (Canham et al. 1990). Direct light includes sunflecks (sudden bursts of light occurring because of gaps in the canopy or cloud cover) which can make the overall light environment extremely variable over the course of the day or season. Over the course of a growing season, the average proportion of direct and diffuse photosynthetically active radiation (PAR) are roughly 0.50 respectively both under a closed canopy and in the open although the total amount of PAR and duration of periods of direct radiation will be greater for the open site (Canham et al. 1990). With many small gaps, such as in an aspen/white spruce mixedwood stand, you get relatively uniform diffuse light at ground level (Lieffers et al. 1999). Diffuse light typically has lower red/far-red ratios than light in the open (Nilsen and Orcutt 1996). As the size of the gap increases the relative amount of direct and diffuse light reaching the center of that gap increases (Lieffers et al. 1999) and the northern edge of the gap is more likely to receive both direct and diffuse light while the southern edge primarily receives diffuse light (Canham et al. 1990).

The structure of a stand can be modified by controlling density and species composition through site preparation, vegetation management, spacing and cleaning practices. In order to promote the growth of white spruce in a mixedwood stand there is a need to increase the amount of light that is available to the understory spruce. This can be done by reducing the density and basal area of aspen or by creating openings within the stand. Openings could be small and very dispersed such as would be achieved via thinning or partial harvesting techniques or could be more concentrated to target the prosperity of single target trees.

Creating large canopy openings in mixedwood stands could have a confounding effect, because with the removal of the aspen, available light increases which promotes the growth of *Calamagrostis canadensis* (Lieffers and Stadt 1994) which can in turn decrease survival and growth of small white spruce. Problems resulting from *C. canadensis* can be especially evident in young white spruce stands where it competes with white spruce for light and delays soil warming (Hogg and Lieffers 1991) and its standing litter in winter can also cause snow press damage (Ländhausser and Lieffers 1998). In fact, even 2-6 year old aspen stands of sucker origin have shown signs of growth limitations from *C. canadensis* (Ländhausser and Lieffers 1998).

Another potential side effect of opening up a mixedwood stand to increased light levels is the possibility of making the stand more susceptible to growing season radiative frost. Radiation frost occurs in open areas on calm, clear nights because there is a large loss of longwave radiation from the ground to the atmosphere that is not replaced by re-radiation back towards the ground as would occur in cloudy conditions (with higher water vapour concentrations which absorb and re-emit longwave radiation) (Stathers 1989; Kimmins

1997) or if there is vegetative cover (Stathers 1989; Kimmins 1997; Langvall and Örlander 2001). The type, height and density of the vegetative canopy affects the rate of night time radiative cooling. Tall, closed canopies of trees reduce the radiative loss from the surface by replacing cold sky with relatively warmer foliage, while short, sparse herbaceous or shrub canopies also restrict radiative loss but not as effectively as tall canopies (Stathers 1989). Low, dense grass canopies trap cold air with the coldest location in the densest layer of vegetation. Removal of the grass allows more mixing of the colder air with warmer surrounding air and exposes the soil surface to more day time heating increasing the heat storage in the soil profile which in turn can be re-radiated at night (Stathers 1989).

Radiative frosts during the growing season contribute substantially to mortality and poor growth of white spruce in Canadian forests (Groot et al. 1997). On calm, clear nights during the growing season the minimum air temperature near the soil surface is strongly influenced by the proportion of the sky `seen´ (Groot et al. 1997). This is known as the sky view factor (SVF) and is a useful term for describing forest openings (it varies from 0 to 1). The soil surface in a completely closed forest canopy has a sky view factor of 0 and the surface of an extensive clearcut has a factor of 1.

The rate of radiative cooling as a result of long-wave radiative loss from the ground increases as the size of opening increases (Langvall and Örlander 2001), especially when the night sky is clear (Stathers 1989). When making openings in a stand, consideration must be given to the trade-off between increased light requirements for increased white spruce vigour and the need to provide protection from summer frost damage. Work done by Groot et al. (1999) in mature stands in Ontario examined effects of opening size on light and temperature under a 40 year old aspen stand in central Ontario and its implication to growth and survival of planted white spruce. To increase total light received within a gap, a large opening must be made (even larger openings are needed in tall stands) because of the solar elevation. The route of nighttime radiative cooling is straight up towards the zenith so large sky views can translate into more potential frost damage (Smith et al. 1997). To maintain the overall energy balance in situations where gaps are situated above a spruce tree, there will be a movement of sensible and latent heat back towards the tree surface from the atmosphere and also heat from the soil and any other surrounding objects will move towards cooler objects. There is also evidence that young evergreen seedlings are more likely to be adversely affected by high light levels the day after a frost event (Örlander 1993). As trees age, frost damage becomes less of a factor and low light levels more of a factor with respect to the growth of trees because of increased requirements for maintenance and respiration. Thus the timing of treatments to promote establishment and vigourous growth of white spruce in mixedwood stands needs to vary with stand age (height) and the structure and density of the individual tree's immediate surroundings.

1.4 Project focus

White spruce is susceptible to frost damage but radiation frost can be reduced by cover from aspen foliage. Aspen can help keep the warm air trapped low to the ground and limit long-wave radiation loss on calm, clear summer nights and thus enhance the survival and vigour of spruce. The cost of this frost protection is reduced light. To date, no published information is available on the effects of opening size in young aspen on frost incidence and on light levels.

This project is comprised of two components. The first component examines the change in light and temperature level in different opening sizes in mixedwood stands. The stands are primarily comprised of aspen trees of approximately 30 years and younger in 3 different height (age) groupings. This first component of the study will be presented in chapter 2. The second component of this project will be presented in chapter 3 and its purpose is to determine if a relationship between the growth of spruce and different light levels exists and if so, to describe this relationship. Finally, in chapter 4, the results presented in chapter 2 and 3 will be brought together to examine possible optimal opening size(s) to improve growth of white spruce within mixedwood stands when the trade-off between increasing light requirements and potential summer frost occurrence is considered.

1.5 References

Alberta Environmental Protection. 1998. The Alberta Forest Legacy – Framework for Sustainable Forest Management. Alberta Environment, Forest Land Division. Edmonton. url: http://www.gov.ab.ca/env/forests/fmd/legacy/legacy.html.

Andison, D.W., and Kimmins, J.P. 1999. Scaling up to understand British Columbia's boreal mixedwoods. Environ. Rev. 7: 19-30.

Aphalo, P.J., and Ballaré, C.L. 1995. On the importance of information-acquiring system in plant-plant interactions. Funct. Ecol. 9: 5-14.

Awada, T., and Redmann, R.E. 2000. Acclimation to light in planted and naturally regenerated population of white spruce seedlings. Can. J. Bot. Vol. 78: 1495-1504.

Beaudry, L., Coupé, R., Delong, C., & Pojar, J. 1999. Plant indicator guide for Northern British Columbia : boreal, sub-boreal, and subalpine biogeoclimatic zones. Land Management Handbook #46. B.C. Min. of For. Res. Branch.

Beckingham, J.D., and Archibald, J.H. 1996. Field guide to ecosites of northern Alberta. Can. For. Ser. Special Report 5. 412 pp.

Bella, I.E. 1986. Logging practices and subsequent development of aspen stands in east-central Saskatchewan. For. Chron. 62(2): 81-83.

Binkley, D., Bell, R, and Sollins, P. 1992. Comparison of methods for estimating soil nitrogen transformations in adjacent conifer and alder-conifer forests. Can. J. For. Res. 22 (6) : 858-863.

Brace, L.G., and Bella, I. E. 1988. Understanding the understory: dilemma and opportunity. In Aspen Symposium '89. Proc. Symp. July 25-27, 1989. Duluth, Minn. R.D. Adams (editor). U.S.D.A. For. Serv. North Cent. For. Exp. Sta., St. Paul, Minn. Gen. Tech. Rep. NC-140. pp 69-86.

Canham, C., Denslow, J.S., Platt, W.J., Runkle, J.R., Spies, T.A., and White, P.S. 1990. Light regimes beneath closed canopies and tree-fall gaps in temperate and tropical forests. Can. J. For. Res. 20: 620- 631.

Carlson, D.W., and Groot, A. 1997. Microclimate of clear-cut, forest interiors, and small openings in trembling aspen forest. Agric. For. Meterology. 87: 313-329.

Chen, H.Y.H. 1997. Interspecific responses of planted seedlings to light availability in interior British Columbia: survival, growth, allometric patterns, and specific leaf area. Can. J. For. Res. 27: 1383-1393.

Coates, K.D., and Burton, P.J. 1999. Growth of planted tree seedlings in response to ambient light levels in northwestern interior cedar-hemlock forests of British Columbia. Can. J. For. Res. 29: 1374-1382.

Comeau, P.G. 2001. Relationships between stand parameters and understorey light in boreal aspen stands. B.C. J. Ecosys. Man. Vol. 1 No. 2: 1-8

Comeau, P.G., Braumandl, T.F., & Xie, C. 1993. Effects of overtopping vegetation on light availability and growth of Englemann spruce (*Picea engelmannii*) seedlings. Can. J. For. Res. 23: 2044-2048.

Constabel, A.J., and Lieffers, V.J. 1996. Seasonal patterns of light transmission through boreal mixedwood canopies. Can. J. For. Res. 26: 1008-1014.

Daniel, T.W., Helms, J.A., & Baker, F.S. 1979. Principle of silviculture. McGraw-Hill. New York. 500 pp.

David, A.J., Zasada, J.C., Gilmore, D.W., & Landhäusser, S.M. 2001. Current trends in the management of aspen and mixed aspen forests for sustainable production. For. Chron. 77(3): 525-532.

Day, R.J., and Bell, F.W. 1988. Development of crop plans for hardwood and conifer stands on boreal mixedwood sites. *In* Samoil, J.K., editor. Management and utilization of northern hardwoods. Information Report. pp.87-98. NOR-X-296 Northern Forestry Centre 163 pp.

Dobbs, R.C. 1976. White spruce seed dispersal in central British Columbia. For. Chron. 52: 225-228.

Duchesneau, R., Lesage, I., Messier, C., & Morin, H. 2000. Effects of light and intraspecific competition on growth and crown morphology of two size classes of understory balsam fir saplings. For. Ecol. Man. 5071: 1-11.

Greene, D.F., Zasada, J. C., Sirois, L., Kneeshaw, D., Morin, H., Charron, I., & Simard, M.-J. 1999. A review of the regeneration dynamics or North American boreal forest species. Can. J. For. Res. 29: 824-839.

Groot, A. 1999. Effects of shelter and competition on the early growth of planted white spruce (*Picea glauca*). Can. J. For. Res. 29: 1002-1014.

Groot, A., Carlson, D.W., Fleming, R.L., & Wood, J.E. 1997. Small openings in trembling aspen forest: microclimate of white spruce and trembling aspen. NODA/NFP Technical Report TR-47.

Groot, A., and Carlson, D.W. 1996. Influence of shelter on night temperatures, frost damage, and bud break of white spruce seedlings. Can. J. For. Res. 26: 1531-1538.

Haeussler, S., Coates, D., & Mather, J. 1990. Autecology of trembling aspen. In Autecology of Common Plants in British Columbia: A literature review. FRDA Report 158. 130-138.

Hogg, E.H., and Lieffers, V.J. 1991. The impact of *Calamagrostis canadensis* on soil thermal regimes after logging in northern Alberta. Can. J. For. Res. 21: 387-394.

Kelty, M.J., Larson, B.C., & Oliver, C.D. 1992. The ecology and silviculture of mixed-species forests. Kluwer Academic Publishers. Netherlands 287 pp.

Kimmins, J.P. 1997. Forest ecology a foundation for sustainable management. Prentice-Hall, Inc. New Jersey. 596 pp.

Kobe, R.A., and Coates, K.D. 1997. Models of sapling mortality as a function of growth to characterize interspecific variation in shade tolerance of eight tree species of northwestern British Columbia. Can. J. For. Res. 27: 227-236.

Kozlowski, T.T., and Pallardy, S.G. 1997. Physiology of woody plants. Academic Press Inc. San Diego. pp.87-132.

Lamontagne, M. , Margolis, H., & Bigras, F. 1998. Photosynthesis of black spruce, jack pine, and trembling aspen after artificially induced frost during the growing season. Can. J. For. Res. 28: 1-12.

Landhäusser, S.M., and Lieffers, V.J. 1998. Growth of *Populus tremuloides* in association with *Calamagrostis canadensis*. Can. J. For. Res. 28: 396-407.

Lieffers, V.J., Pinno, B.D., and Stadt, K.J. 2002. Light dynamics and free-to-grow standards in aspen-dominated mixedwood forests. For. Chron. 78(1): 137-145.

Lieffers, V.J., Messier, C., Stadt, K.J., Gendron, F., and Comeau, P.G. 1999. Predicting and managing light in the understory of boreal forests. Can. J. For. Res. 29: 796-811.

Lieffers, V.J., Stadt, K.J., & Navratil, S. 1996. Age structure and growth of understory white spruce under aspen. Can. J. For. Res. 26: 1002-1007.

Lieffers, V.J., and Beck Jr., J.A. 1994. A semi-natural approach to mixedwood management in the prairie provinces. For. Chron. 70: 260-264.

MacDonald, G.B. 1996. Silviculture of temperate & boreal broadleaf conifer mixtures. Land Management Handbook #36. BC Ministry of Forests- Research Branch. pp 102-113.

MacIsaac, D.A., and Navratil, S. 1996. Silviculture of temperate & boreal broadleaf conifer mixtures. Land Management Handbook #36. BC Ministry of Forests- Research Branch. 23-34.

Man, R., and Lieffers, V.J. 1999. Are mixtures of aspen and white spruce more productive than single species stands? For. Chron. 75: 505-513.

Messier, C., Doucet, R., Ruel, J. Claveau, Y., Kelly, C., and Lechowicz, M.J. 1999. Functional ecology of advance regeneration in relation to light in boreal forests. Can. J. For. Res. 29: 812-823.

Navratil, S. 1996. Silviculture of temperate & boreal broadleaf conifer mixtures. Land Management Handbook #36. BC Ministry of Forests- Research Branch. pp 35-46.

Nilsen, E.T., and Orcutt, D.M. 1996. Physiology of plants under stress: abiotic factors. John Wiley & Sons Inc. New York. pp. 401-444.

Oliver, C.D., and Larson, B.C. 1996. Forest stand dynamics. Update edition John Wiley & Sons, Inc. New York. pp. 9-88.

Örlander, G. 1993. Shading reduces both visible and invisible frost damage to Norway spruce seedlings in the field. Forestry 66(1): 27-36.

Peterson, E.B., and Peterson, N.M. 1995. Aspen managers' handbook for British Columbia. Canada-British Columbia Partnership Agreement on Forest Resource Development. FRDA II. FRDA Report 230. Victoria, BC, Canada.

Rowe, J.S. 1972. Forest regions of Canada. Canadian Forestry Service. Publication No. 1300.

Smith, D.M., Larson, B.C., Kelty, M.J., & Ashton, P.M.S. 1997. The practice of silviculture: applied forest ecology. John Wiley and Sons, Inc. New York. 537 pp.

Spittlehouse, D.L., and Stathers, R.J. 1990. Seedling Microclimate. Land Management Report #65 BC Ministry of Forests.

Sprugel, D.R., Brooks, J.R., & Hinckley, T.M. 1996. Effects of light on shoot geometry and needle *Abies amabilis*. Tree Physiology 16: 91-98.

Stathers, R.J. 1989. Summer frost in young forest plantations. FRDA Report #73.

Stewart, J.D., Hogg, E.H, Hurdle, P.A.,Stadt, K.J.,Tollestrup, P., & Lieffers, V.J. 1998. Dispersal of white spruce seed in mature aspen stands. Can.J. Bot. 76: 181-188.

Stewart, J.D., Landhäusser, S.M., Stadt, K.J., & Lieffers, V.J. 2000. Regeneration of white spruce under aspen canopies: seeding, planting and site preparation. West. J. Appl. For. 15(4): 177-182.

Thorpe, J.P. 1992. The ecology and silviculture of mixed-species forests. Kluwer Academic Publishers. Netherlands 287 pp.

2. Effects of size of circular openings on light and temperature levels under young trembling aspen stands.

2.1 Introduction

Trembling aspen and white spruce mixtures are often found on upland mesic sites in the boreal forests of Western Canada (Rowe 1972; Beckingham and Archibald 1996). Currently there is an increased desire to maintain these mixedwood stands rather than undertake costly and often unsuccessful conversions to pure softwood stands (Lieffers and Beck 1994). The maintenance of mixedwood stands can benefit biodiversity, promote long term soil and site productivity and reduce risks of frost and insect damage (Comeau 1996; Man and Lieffers 1999) and more closely emulates the natural disturbance approach to management of these specific site types.

Stand regeneration and development following disturbance in a mixedwood stand is dependent on the type as well as the intensity of the disturbance. The origin of many mixedwood stands can be traced to wildfires (Lieffers and Beck 1994) but they also originate from harvesting activities, windstorm damage and insect defoliation. In the case of low to moderate intensity fires and large clearcuts in the absence of site preparation and planting, trembling aspen dominated stands often result. Although the regeneration of spruce tends to be more unpredictable than aspen (Greene et al. 1999), by utilizing partial cuts, strip cuts or small clearcuts where there is an available white spruce seed source, stands with a larger component of white spruce can be produced.

Underplanting and/or understory protection of spruce or site preparation and spruce planting can also lead to stands with a larger proportion of white spruce.

Regardless of the proportion of trembling aspen and white spruce within a young mixedwood stand, the growth of aspen tends to be superior to spruce in the early stages of stand development because of its more aggressive invasion capabilities and vigourous juvenile growth (Haeussler et al. 1990; Peterson and Peterson 1995; Greene et al. 1999; David et al. 2001). White spruce is able to survive and grow very slowly in low light levels beneath an aspen canopy as the canopy allows diffuse light penetration (Lieffers et al. 1999) and during the aspen leaf-off period in the early spring the spruce is able to utilize the higher available light levels (Constabel and Lieffers, 1996).

The ability of the white spruce to survive at low light levels allows it to fit well into the natural development of mixedwood stands. During the first 15 to 25 years of stand development, the leaf area of the stand (that is mostly comprised of trembling aspen) increases until such a time as the competition for available light becomes so severe that self-thinning of the aspen results (Geiger 1965; Lieffers et al. 2002). Understory light levels can be as low as 5 % of open sky values but are typically in the 10-20 % range (Lieffers et al. 2002). Self-thinning leads to the formation of gaps in the canopy that may benefit spruce that has been able to survive at low light levels in the understory or the gaps may provide opportunities for establishment of spruce regeneration (Stewart et al. 1998).

If the management objective in young mixedwood stands is to promote the early growth and vigour of the white spruce component, there is a need to provide more light to improve both photosynthesis and growth rates. One approach for increasing the amount of light reaching spruce crop trees is to create small openings in order to increase light levels. Currently however, besides what could be predicted by light models, there is little information to guide decisions regarding the ideal radius of these openings.

White spruce shoots have maximum photosynthetic rates between 40 and 60% of full sunlight (Spittlehouse and Stathers 1990; Coates and Burton 1999) and levels up to 100% of full sunlight are needed for maximum diameter and stem volume growth (Comeau et al. 1993; Coates and Burton 1999) suggesting that, at least on a theoretical basis, larger openings are more beneficial for the best overall growth of spruce. There are many reasons why creating very large openings surrounding white spruce stems may not result in improved white spruce growth and vigour. Four primary reasons are: 1) large opening may negatively impact stem quality with poorer stem form, larger branches and high stem taper; 2) large openings may favour aspen re-sprouting and growth resulting from increased red/far-red ratios (FitzGerald and Hoddinott 1983) and aspen are a more vigourous competitor than spruce; 3) large openings also can lead to the promotion of growth of *Calamgrostis canadensis* which can be a vigourous competitor with white spruce, and together with increased cover of other species it can lead to decreased survival and growth of spruce (Lieffers and Stadt 1994); and, 4) large openings can increase the risk of the occurrence of growing season radiative frost (Stathers 1989; Groot and Carlson 1996).

While the relative proportions of direct and diffuse photosynthetically active radiation (PAR) within a large opening or under a closed canopy are basically equal when considered over the course of a growing season, the total quantity of PAR transmittance (the proportion of below canopy to open sky) and the duration of periods of direct radiation increases within openings in relation to the size of the opening (Canham et al. 1990). The contribution that diffuse light makes to the seasonal PAR values decreases uniformly with increasing distance from the center of the gap while the direct beam contribution is offset to the north of gap center (Canham et al. 1990).

The high latitude of Canadian boreal forests means that solar elevations are relatively low even during the summer months. Small gaps (especially in taller forest stands) will likely not receive direct solar radiation if sunflecks of very short duration are discounted. Larger gaps or gaps within shorter stands receive direct radiation from such a low solar elevation that the location of maximum radiation is usually offset to the north of gap center (Canham et al. 1990; Lieffers et al. 1999).

Recruitment of trees, with varying shade tolerance, is generally highest on the southern edge of the gap and in areas with higher forest floor disturbance (Wright et al. 1998), especially within medium and large gaps, but longer term survival and growth of these trees may be improved nearer to the center or the northern edge of the gap (Schupp 1995; Coates 2002). Openings will therefore need to be large enough to increase light to improve overall long term survival, but not so large that a harsh microclimate results which makes initial seed and seedling establishment problematic.

The many small gaps in a deciduous overstory produce relatively uniform diffuse light at ground level (Lieffers et al. 1999). Light quality is also influenced by the deciduous overstory with understory positions experiencing lower red/far-red ratios than light in the open (Nilsen and Orcutt 1996) or light under a coniferous canopy (Ross et al. 1986). In diffuse or low light conditions, plants adapt by growing towards light as a response to the increased proportion of far-red light (Nilsen and Orcutt 1996). The specific leaf area of needles growing under diffuse light conditions is increased with needles tending to be thin and broad to more efficiently capture available light (Awada and Redmann 2000; Chen 1997; Messier et al. 1999).

Because plants rarely compete for light in the absence of competition for water and nutrients, it is difficult to separate these interactions (Cannell and Grace 1993). Consequently light measurements should only be considered as a surrogate of competition. If small or medium sized openings are created in tall stands, the benefit from increases in light may be compromised because the position of increased light is offset from the location of reduced competition for water and nutrients (Lieffers et al. 1999).

Once openings are created, there will be some movement by the crowns adjacent to the gap to expand into the available space. Most western boreal species with their relatively narrow crowns tend to have limited horizontal expansion making re-invasion less of an issue than it appears to be in the eastern boreal forests (Lieffers et al. 1999). Studies in 15-18 meter tall forests in the northeastern United States have found average horizontal expansion rates into gaps of 14 cm/year for red oak and 6 cm/year for white pine (Hibbs 1982). Valverde and Silvertown (1997) found that the rate of gap closure occurred more quickly in the beginning and decreased over time. This is in agreement with Runkle (1998) who found that the rate of gap closure decreased over time.

Creating openings within stands can lead to increases in the incidence of summer radiative frosts. In the open, on calm, clear nights during the growing season, occurrence of frost becomes more common because there is little to impede the loss of longwave radiation to the relatively colder atmosphere as well as little wind to help mix the warmer air further above the ground with the colder air close to the ground (Stathers 1989; Kimmins 1997). If there is some overhead cover then some of the longwave radiation is re-radiated back towards the ground (Stathers 1989; Kimmins 1997; Langvall and Örlander 2001) moderating the temperature environment and the energy balance can be maintained without excessive cooling of plant tissues which would occur without this re-radiation (Smith et al. 1997). Groot and Carlson (1996) found that during calm, clear nights in May and June, that the average air temperature was 6°C warmer under an intact 40 year old aspen canopy than in a clearcut but only 1°C warmer under cloudy conditions. Shelterwood systems can also provide protection from frost with more protection at higher retention levels (Langvall and Örlander 2001; Langvall and Löfvenius 2002).

Injuries that result from low temperatures are associated with ice crystal formation within plant cells and subsequent damage to chloroplast membranes (Gillies and Binder 1996). Discolouration of needles is often the first visual sign of damage from frost and results from breakdown of chlorophyll (Lundmark and Hällgren 1987; Grossnickle 2000) which in turn leads to a reduction in net photosynthesis.

Groot and Carlson (1996) found that the likelihood of growing season frost injury to spruce planted under a 40 year old aspen stand increases with the size of the opening, especially in terms of its relationship to the surrounding stand height.

Cochran and Berntsen (1973) found increased mortality in both lodgepole pine and ponderosa pine in response to a low night temperature of –7.8°C but determined that once seedlings survived the initial growing season they were more resistant to temperatures as low as –9.4°C. Black spruce shows a decrease in freezing tolerance of established seedlings from the start of bud swelling through the period of new shoot elongation (Bigras and Hébert 1996). Moderate freezing levels (air temperatures of –2.5°C) in mid August in southeastern Wyoming caused only a minor and reversible decrease in photosynthetic rates of 1-year old needles of mature Englemann spruce shoots while -5°C caused an irreversible reduction in photosynthetic rate as well as apparent quantum yield and photosynthetic efficiency (DeLucia and Smith 1987). Gillies and Binder (1996) found more injury in newly flushed than in dehardened white spruce foliage exposed to freezing temperatures, although both did experience more injury than hardened foliage.

When freezing temperatures are followed by exposure to high light the damage is significantly worse (Lundmark and Hällgren 1987; Örlander 1993; Gillies and Binder 1996; Langvall and Örlander 2001). This difference is attributed to photoinhibition and photodamage. Soil moisture status also has an effect on frost events. On calm clear nights when soils are wet, there is less of a difference between minimum temperatures experienced within clearcut and dense shelterwood areas (Langvall and Löfvenius 2002). In dry surface soil conditions larger openings show significantly lower minimum temperatures than under dense shelterwood (Langvall and Löfvenius 2002) or under a 40 year old aspen canopy (Groot and Carlson 1996). This can be explained by the effects of latent heat transfer as apposed to sensible, with wetter soils better able to moderate temperatures without large changes in plant tissue temperature.

The height and density of the surrounding canopy within which openings are made may also affect the temperature conditions within created gaps. Taller canopies replace a larger proportion of the sky view with foliage and stems leading to greater reduction of longwave radiation losses. Taller canopies, and larger stems in general, will absorb more radiation during the day as well, this will be available for re-radiation back towards the cooler surface at night. On calm clear nights the foliage at the top of a taller canopy is surrounded by warmer air aloft that tends to be well mixed and warmer than the air near the ground (Stathers 1989). This allows re-radiation towards the ground, moderating the understory temperature environment. With denser canopies there is less cold sky within the view and longwave radiation loss is reduced (Stathers 1989) again moderating the temperature.

The objective of this component of the study is to determine how light transmittance and the occurrence of cold temperatures change with opening size and whether the change is consistent (both at a consistent 1 meter height and as you progress vertically upwards within the opening) between three different height groupings and between sites in Fort St. John, B.C. and Slave Lake, AB. Seasonal transmittance values and temperature levels are compared for openings ranging from intact forest to circular openings with diameters that are twice the width of the height of the surrounding stand.

2.2 *Materials and Methods*

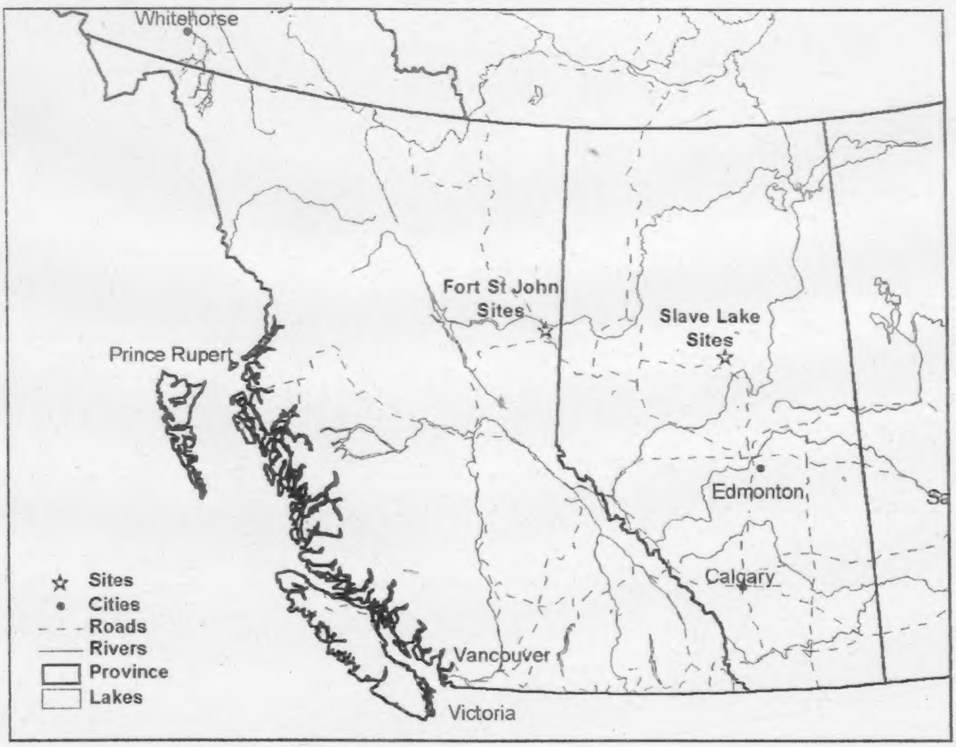

Whitehorse
Fort St John Sites
Slave Lake Sites
Prince Rupert
Edmonton
Calgary
Vancouver
Victoria
☆ Sites
● Cities
Roads
Rivers
Province
Lakes

Figure 2.1. General location of the selected study sites near Fort St. John, B.C. and near Slave Lake, AB.

Examination of the effects of opening radius on light levels was carried out at two locations (Figure 2.1): the first site is located northeast of Slave Lake, Alberta (55° 30′ N, 114° 30′ W); and the second site is located near Fort St. John in northeastern B.C. (56° N, 120° 30′ W). Specific locations of individual stands are shown in table 2.1.

Table 2.1. Locations and average stand characteristics of 18 individual stands near Slave Lake, AB and near Fort St. John, B.C.

General location	Block	Latitude (N)	Longitude (W)	Elevation(m)	Stand height (m)	Stand density (sph)
Slave Lake	66N	55° 30′ 52″	113° 47′ 17″	750	3	28,700
Slave Lake	66S	55° 30′ 48″	113° 47′ 26″	730	2	14,880
Slave Lake	69	55° 30′ 24″	113° 45′ 34″	760	3.3	37,700
Slave Lake	14A	55° 25′ 58″	114° 34′ 07″	790	4	25,000
Slave Lake	14B	55° 26′ 05″	114° 34′ 06″	820	4	20,100
Slave Lake	Fawcett	55° 19′ 08″	114° 04′ 23″	625	4.5	21,680
Slave Lake	35A	55° 30′ 25″	114° 16′ 48″	790	7.7	22,200
Slave Lake	35B	55° 30′ 24″	114° 17′ 03″	760	7.6	18,600
Slave Lake	Husky	55° 28′ 05″	114° 10′ 33″	760	7	17,200
Fort St. John	Ltsps-1	55° 58′ 15″	120° 28′ 05″	700	2	20,800
Fort St. John	Ltsps-2	55° 58′ 48″	120° 27′ 45″	700	2	10,200
Fort St. John	Ltsps-3	55° 58′ 19″	120° 28′	700	2	15,900
Fort St. John	CLR2	55° 59′ 12″	120° 29′ 30″	780	4	27,200
Fort St. John	Clear	55° 59′ 06″	120° 29′ 24″	780	3.5	29,500
Fort St. John	Mud	56° 04′ 27″	120° 47′ 36″	720	4	25,400
Fort St. John	367	55° 57′ 54″	120° 29′ 51″	710	7	14,600
Fort St. John	403A	55° 58′ 37″	120° 28′ 03″	730	7.5	16,500
Fort St. John	403B	55° 59′ 12″	120° 29′ 30″	720	7.5	21,500

Effects of opening size on soil and air temperature were examined at selected study sites located near Slave Lake, Alberta. Sites were specifically chosen to be consistent in their moisture and nutrient regimes (mesic and medium nutrient sites were chosen). At both locations, stands were dominated by trembling aspen (*Populus tremuloides* Michx.) with minor amounts of white spruce (*Picea glauca* (Moench) Voss) in the understory. In order to find enough sites, we had to choose some sites that were slightly wetter than mesic, and these sites were characterized by the additional occurrence of minor amounts of balsam poplar (*Populus balsamifera* L.) and white birch (*Betula papyrifera* Marsh.). Closed canopied stands dominated by aspen were selected since this type of stand tends to have a more even height distribution which was desirable to limit variation between openings

Openings of increasing size were created in aspen stands selected to represent each of three height classes (2-3 m, 3.5-5 m, and 6-8 m). Sky view factor (SVF) is the amount of sky that can be seen when looking up. For a circular opening, it can be calculated as:

$$\mathbf{SVF = \cos^2 (\tan^{-1}(2H/D))}$$

where H is the forest height and D is the diameter of the circular opening (Oke 1987) (Table 2.2). The ability to see more sky is influenced by the height of the surrounding trees. The size of the opening therefore has to increase when you have a taller forest to maintain a constant range of sky view factors between stands.

Table 2.2. Opening diameters (m) required in stands of differing heights (m) to achieve different values of sky view factor

Forest height (m)	Sky view factor 0	0.1	0.2	0.3	0.4	0.5
3	0	2	3	4	5	6
6	0	4	6	8	10	12
9	0	6	9	12	15	18

In each stand, 6 plot centers were established such that each center was located at least four times the average stand height apart to ensure that each plot was independent of its neighbours. Within each stand, an opening size that corresponds to SVFs of 0, 0.1, 0.2, 0.3, 0.4, 0.5 (as measured at ground level) was randomly assigned to each pre-established plot center. Three replicates of each stand height were established and this design was duplicated in each of the two locations (3 stand heights with 6 SVFs being replicated 3 times totaling 54 treatments at each location).

SVF was calculated based on the stand geometry at ground level. During analysis SVF was corrected to account for the measurement height at which individual light or temperature measurements were taken. This correction had a much greater impact in openings in shorter stands than in taller stands. The size of the holes cut was based on stem to stem distance rather than crown to crown distances.

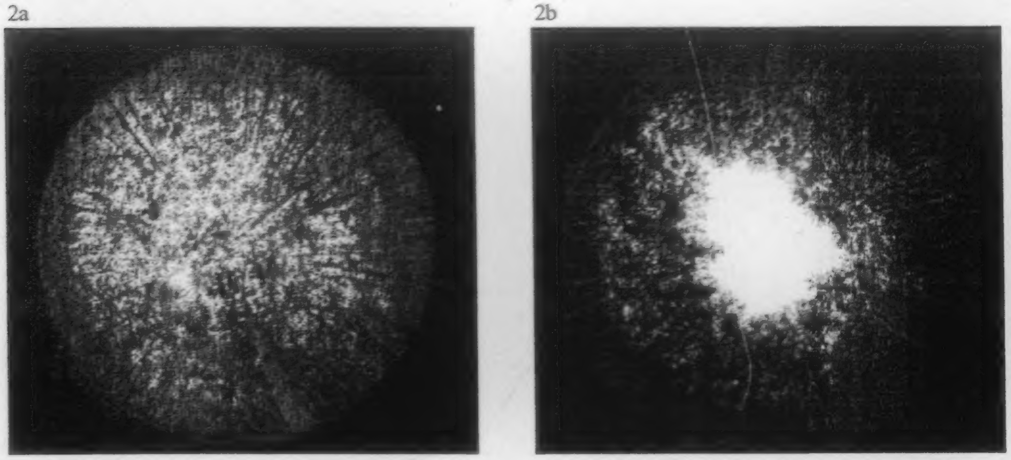


Figure 2.2. Examples of hemispherical photographs taken in a 7.7 meter tall stand near Slave Lake before (2a) and after treatment (2b) with a small circular opening size (2.5.m radius) giving a SVF of 0.095 at ground level and 0.12 at a 1 meter measurement height.

Both components of this study require the measurement of light levels. Two different methods were used to measure light transmittance: hemispherical photography; and LiCOR LAI -2000 plant canopy analyzers.

Hemispherical photographs were taken using a Nikon Coolpix 990 digital camera with a 185 ° field-of-view lens mounted on a tripod (Figure 2.2). Photographs were taken from plot center at one meter above ground level with the top of the camera oriented northward. The camera was set to slightly overexpose the photographs to ensure good contrast between sky and foliage. To prevent glare from direct sunlight, photos were taken early in the morning or later in the evening or under conditions of uniform cloud cover. Some photos had to be pre-processed using Photoshop® 5.5 to increase distinction between foliage and sky when sky conditions were not as uniform as originally thought. Photos were each individually thresholded using the Spot Light Interception Model (SLIM) by manually choosing and marking parts of the photo as being sky or foliage to direct the program in its conversion of individual pixels to black or white (binary) information. The photographs were then analyzed by SLIM to calculate the seasonal percent light transmission with respect to the location of the camera (Comeau et al. 2002)(Figure 2.3). This seasonal transmittance is calculated by considering the location of the sun throughout the season, partitioning total photosynthetic photon flux density (PPFD) into direct and diffuse components and estimating the amount of each component that penetrates to the plot center. The direct PPFD is assumed to come from the location of the sun and the diffuse PPFD is assumed to be distributed according to the standard overcast model which assumes that the sky is 2.2 to 2.3 times brighter directly overhead compared to the horizon (Comeau et al. 2002). Seasonal transmittance was calculated for the period June 1 to October 1, which roughly corresponds to the period of leaf-on for aspen. Default hourly percentages of clear versus overcast sky conditions were used to determine total PPFD values throughout this period.

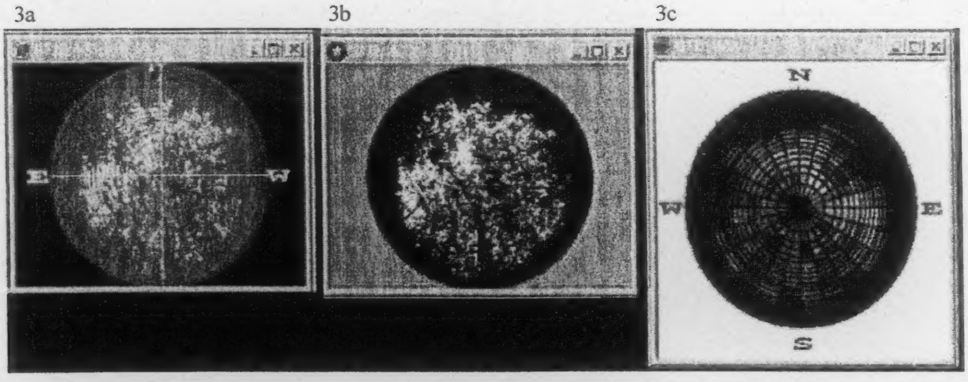


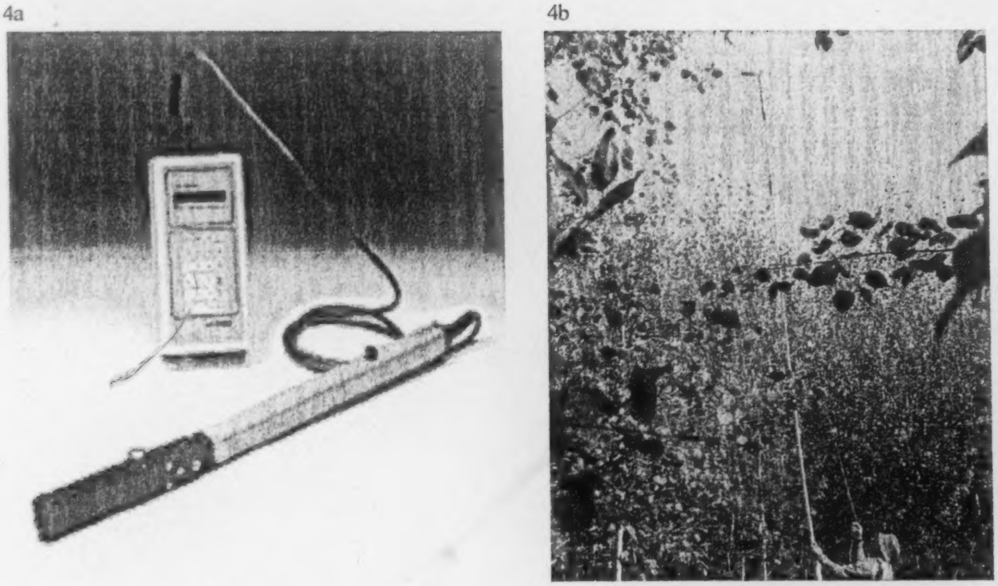
Figure 2.3. Digital photograph of an untreated plot. In 3a the photo is automatically registered and gridded by the SLIM model, in 3b after thresholding the photo, SLIM determines what portions in the view are sky and what portions are foliage and tree stems and in 3c the solar path has been overlain and below canopy radiation is determined by using the gap fraction calculated by thresholding the photograph and estimating the penetration of direct and indirect light through the canopy

The LAI-2000 plant canopy analyzer can be used under overcast sky conditions or within a period during the day when the sun is not directly within its view. This can be done by using a view restrictor on the sensor and taking readings from the same spot at different times during the day when the sun is in different locations in the sky (i.e., taking readings in the south and west directions during the morning and pointing towards north and east directions late in the afternoon).

The LAI-2000 plant canopy analyzer with a LAI-2050 optical light sensor attached is designed to estimate leaf area index but it can also be used to estimate light transmission at a given position within the forest. It has a 150° field-of-view and a special sensor to measure the proportion of open sky light reaching a point from five different angles in the sky. LAI-2000 plant canopy analyzer measurements were taken, using a 90° view restrictor, in each of 4 cardinal directions. When using the LAI-2000, paired measurements are needed: one measurement taken at your point of interest in the forest;

and the other taken simultaneously in the open. These paired readings were accomplished by use of two LAI-2000 analyzers. The two analyzers were used in one of two ways: either by changing directional positioning within a plot and in the open simultaneously (using radio contact); or, by positioning one analyzer in the open on a tripod oriented in a given direction and moving the other analyzer from plot to plot and completing all measurements in one direction. Diffuse non-interceptance (DIFN) values were calculated using the C2000 program on the LAI-2000 data files. DIFN is a value that represents the proportion of light reaching the top of a canopy that penetrates to the understory location (LI-COR, Inc. 1992). The LAI-2000 has an optical filter that blocks radiation less than 490 nm and consequently the resulting DIFN calculation is a measure of the absorption of diffuse, shortwave radiation (LI-COR, Inc. 1992). DIFN has been well correlated to the total light transmitted over the growing season through forest canopies (Comeau 2000, Gendron et al.1998, Lieffers et al. 1999, Comeau et al. 1998). During analysis, the four pairs of directional DIFN readings were averaged to compute the final plot transmittance and the measurements from the fifth ring were masked to better correspond to the portion of the sky that was considered in the analysis of the hemispherical photographs.

LAI-2000 measurements were taken from plot center at a 1 m height before and after the openings are cut. Additionally, after openings were created the LAI-2000 was attached to a 9-meter height pole and light readings were taken at 2 meters and again at each meter above this point until the height of the surrounding aspen stand was reached (Figure 2.4).


4a

4b

Figure 2.4. The LAI- 2000 with a 2050 optical light sensor. In 4a the basic unit and in 4b the LAI-2000 is attached to a 9 meter height pole and readings are taken every 1m above plot center to establish a vertical light profile.

Transmittance measurements obtained using hemispherical photographs analyzed using SLIM and those obtained using LAI-2000 plant canopy analyzers were compared using linear regression techniques to determine the relationship between the two measurement techniques. The two methods are highly correlated (R^2=0.905) but the DIFN measurements appear to underestimate transmittance for low light situations when compared to seasonal transmittance determined from hemispherical photos. To test whether the slope of the regression is significantly different from 1 (which would result if the two methods gave identical measurements) a t-test was performed and it was determined that the relationship has a slope that is significantly different than 1 and an intercept term that is significantly different from 0 (Figure 2.5).

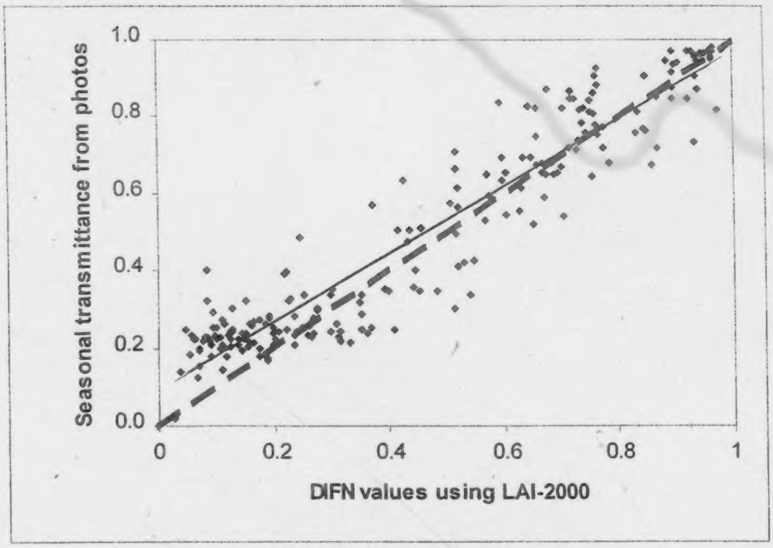


Figure 2.5 Relationship between growing season transmittance measured with hemispherical photographs and the SLIM program and DIFN values calculated from measurements taken with LAI-2000. The dashed line show a 1:1 relationship and the solid line can be described by the equation: growing season transmittance = 0.09331+ 0.8748*DIFN; R^2=0.905. The intercept is significantly greater than 0 ($p<0.0001$) and the slope is significantly different than 1 ($p<0.0001$).

To determine the temperature regime within these created openings, Lakewood Systems TP-X thermistor temperature probes were used. These probes were interfaced to IP-T input plugs which convert the thermistor's resistance to a 0 to 2.5 voltage output. The thermistors were attached to LE7110 data loggers and set up within a sub-sample of the openings in the Slave Lake area. Lakewood LS-4 data logger software was used to convert the voltage to temperature in degrees Celsius using least square curve fitting of a fifth degree polynomial. The temperature probes were constructed and tested immediately prior to field use and again afterwards. The testing of the probes after field use was done by simultaneously exposing the temperature probes to an ice bath.

Temperature sensors were installed, within 15 of the 54 openings near Slave Lake, at a 15 cm depth in the soil and 20 cm and 100 cm above the ground. Data loggers were programmed to sample temperatures at each sensor once every minute and record hourly minimum and maximum and average temperatures. Temperature was recorded throughout the growing season (from May 29, 2002 to September 16, 2002). To protect the data loggers from the environment, rodents and other wildlife, both wooden and plastic boxes were used to enclose the units. Electrical cable covering was used to protect any exposed wires and plumbers compound was used to close off the openings that had been made into boxes to feed cable through. Temperature probes were not shielded from direct sunlight as shielding reduces the ability of sensors to detect radiative cooling. Because of the lack of shielding, both maximum and average temperatures may be inflated in situations where direct sunlight was striking the probe. Consequently analysis focuses on recorded hourly minimum air temperatures. The exception to this was in calculations of growing degree days (GDD) where the average hourly temperature was used to closer simulate typical GDD calculations which use the average between the difference in daily minimum and maximum air temperatures.

Leaf and air temperature are not necessarily consistent with the leaf itself being able to moderate the temperature within its immediate vicinity. This is particularly the case during periods of high irradiance and low wind speeds as leaves are able to moderate temperatures within the boundary layer surrounding them. During periods of lower irradiance, air and leaf temperatures tend to be more similar (Martin et al. 1999). Under calm, clear conditions leaf temperatures have been shown to be lower than air temperatures by 1-3°C (Leuning and Cremer 1988). Differences between leaf and air temperatures are often greater with larger leaf size and when needles are tightly packed along branches as they are in sun shoots (Jarvis et al. 1976)

A comparison of leaf and air temperature was carried out. Leaf temperature was measured using a Raytek all temperature handheld thermocouple thermometer with an infrared probe. Air temperature was measured with a Lakewood TP-X thermistor temperature probe attached to a LE7110 data logger which was set to record the temperature every minute throughout the period from 9:00 pm on May 11, 2002 through 6:00 pm on May 12, 2002. The probe that measured air temperature was located 15 cm from the plant surface and leaf temperature was measured by placing the infrared probe immediately adjacent to the leaf surface. Leaf temperature was taken approximately every 4 hours throughout the period and a time-matched air temperature was obtained from the LE7110 file using LS-4 conversion software.

Information to characterize the general stand conditions was obtained by establishing five 3.99 m circular plots between created openings in each stand. Each tree within the plot that was taller than breast height (1.3 m) was measured for diameter at breast height and its species noted.

2.2.1 Data Analysis

Data analysis was completed using SAS Version 8.1 (SAS Institute Inc. 1999-2000). Multiple linear regression analysis was used to examine the relationship between post-treatment light transmittance and pre-treatment transmittance and sky view factor.

Seasonal transmittance, as calculated from analysis of the hemispherical photographs taken at a height of 1 meter from plot centers before and after opening establishment, was used in this analysis. Logarithmic transformation of the dependent variable was used to achieve homogeneity of variances. Residual plots (Figure 2.6) indicate that residuals of values predicted by the log transformed data show a good scatter of points around zero with the possible exception of the model representing the Fort St. John plots on their own (center 2 graphs in Figure 2.6).

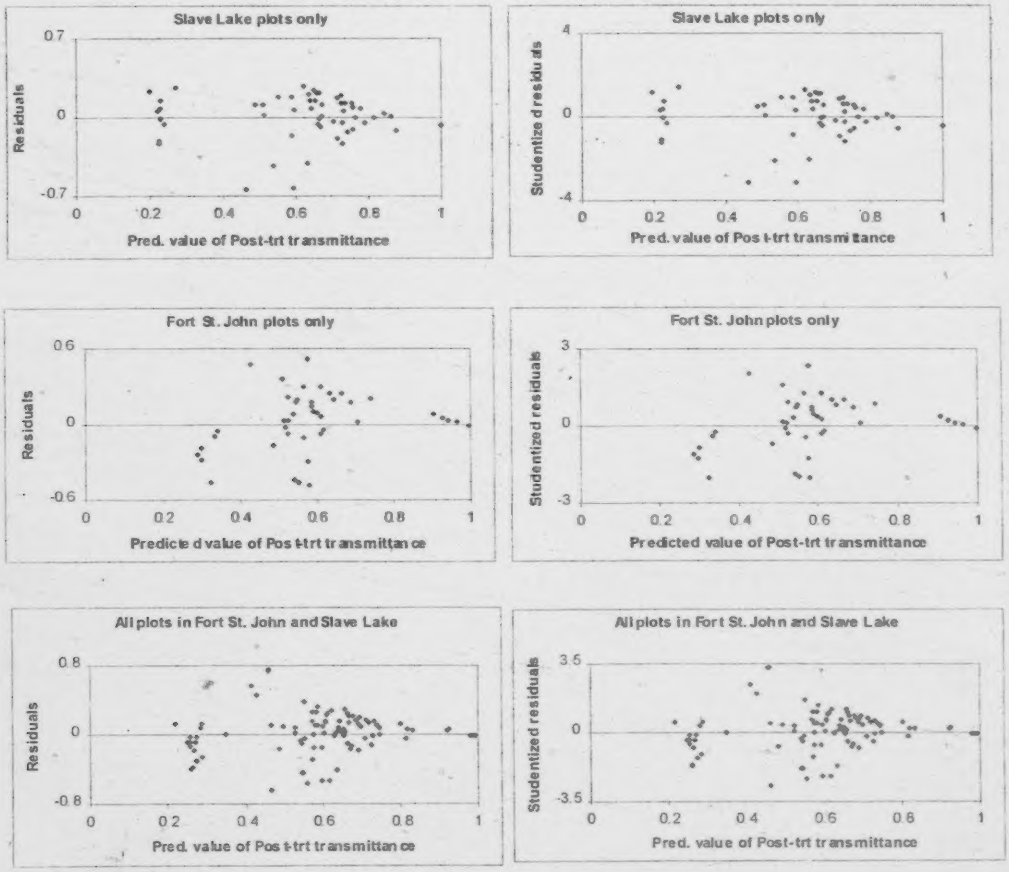
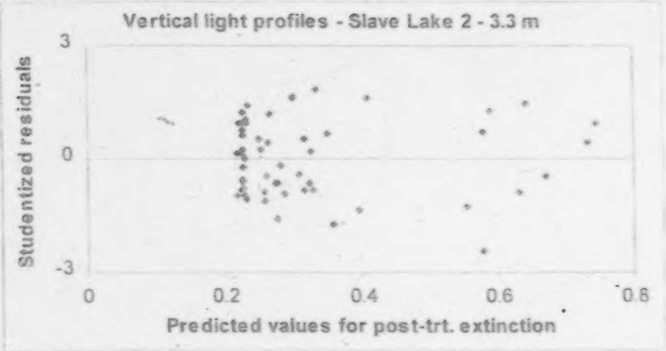


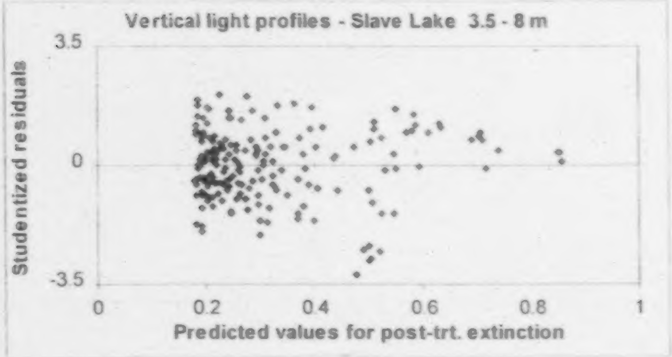
Figure 2.6. Scatterplot of residuals and studentized residual (corrected by standard error) values and predicted values of post-treatment transmittance as produced from the relationships given by the model LnPst-treatment transmittance = LnSVF + LnPre-treatment transmittance for each of the three separate models as represented in figures 2.8-2.10.

Analysis of the vertical light profile also utilized multiple linear regression to examine the relationship between post-treatment light extinction levels (1-transmittance) and the vertical position of the measurement. In this model, DIFN values, calculated from the measurements taken utilizing the LAI –2000 attached to the height pole, were used. Residual plots (Figure 2.7) indicate that the log transformed values show a good scatter of points around zero.

2.7a



2.7b



2.7c

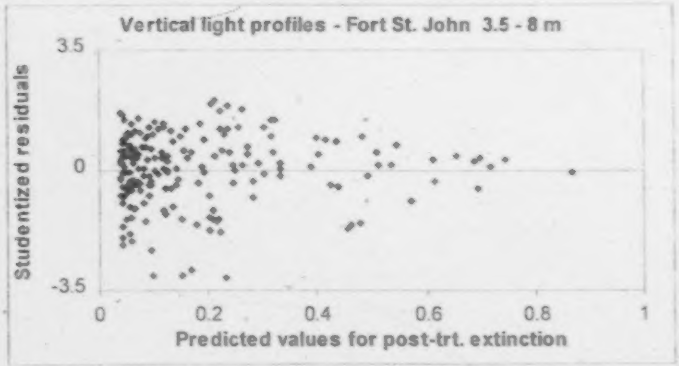


Figure 2.7. Scatterplot of studentized residual values and predicted values of post-treatment extinction as produced from the relationships given by the model LnPost treatment Extinction = LnRelativeHeight + LnSVF for Slave Lake stand heights 2-3.3 m (2.7a); Slave Lake stand heights 3.5-8 m (2.7b); and Fort St. John 3.5-8m (2.7c) as described in Table 2.5 on page 53

PROC GLM in SAS was used to test whether any of the temperature probes were statistically different from each other when immersed in an ice-water bath (using pair-wise t-tests adjusted with Tukey). This test was negative with all probes reading consistently similar temperatures using an α value of 0.05.

A test between temperature measured immediately adjacent to the leaf surface and that measured in the air at the same time using analysis of variance showed that the values obtained using these two methods did not differ significantly ($\alpha = 0.05$). Measurement of air temperature when low temperatures are of interest should give a reasonable estimate of leaf temperatures during clear calm nights.

2.3 Results

2.3.1 Light transmittance at 1 m in relation to opening size and SVF

The stands northeast of Slave Lake, Alberta (Table 2.3a) ranged in height from 2 to 8 meters, stand density ranged from 7,200 to 45,000, stand basal area ranged from 1.2 to 25.3 m^2/ha, and pre-treatment transmittance (based on analysis of hemispherical photographs taken from plot center at 1m height) ranged from 0.12 to 0.68 while the stands near Fort St. John, BC (Table 2.3b) ranged in height from 1.8 to 8 meters, density ranged from 7,500 to 39,500, basal area ranged from 0.8 to 29.5 m^2/ha, and pre-treatment seasonal transmittance ranged from 0.15 to 0.97.

Table 2.3. A summary of characteristics of sampled stands

2.3a - stands northeast of Slave Lake, Alberta

Stand	Height range	Density Range	BA/ha range	Pre-trt seasonal transm. range	Average DBH	Average density	Average BA/ha
66N	2.5 –3.5	21,000 - 36,000	5.9 –9.7	0.20 – 0.51	1.6	28,700	6.9
66S	2.0 –3.0	7,200 – 22,200	1.2 – 5.8	0.24 – 0.68	1.6	14,880	3.6
69	2.5 –3.5	31,000 - 45,000	9.5 – 14.8	0.12 – 0.40	1.8	37,700	12.3
14A	4 – 4.5	19,000 – 33,000	2.1 – 11.0	0.23 – 0.32	1.7	25,000	7.2
14B	3.5 - 4	10,500 – 28,500	3.4 –11.2	0.17 – 0.33	2.6	20,100	8.3
Fawcett	4 - 5	15,200 – 30,200	11.9 – 18.7	0.20 – 0.33	2.5	21,680	13.9
35A	7 - 8	19,000 – 28,000	16.9 – 24.5	0.19 – 0.25	3.0	22,200	21.2
35B	7 - 8	12,500 – 30,000	19.0 –25.3	0.18 – 0.40	3.6	18,600	22.2
Husky	7 - 8	9,000 – 27,000	7.9 – 22.9	0.14 – 0.26	2.9	17,200	14.5

2.3b – stands near Fort St. John, British Columbia

Stand	Height range	Density range	BA/ha range	Pre-trt seasonal transm. range	Average DBH	Average density	Average BA/ha
Ltsps-1	1.8 - 3	11,500 – 26,500	1.5 – 2.3	0.76 – 0.96	1.0	20,800	1.9
Ltsps-2	1.8 - 3	7,500 – 12,000	0.8 – 1.2	0.68 – 0.97	1.1	10,200	1.1
Ltsps-3	1.8 - 3	10,500 – 21,000	1.3 – 2.9	0.55 – 0.91	1.1	15,900	1.7
CLR2	3 - 5	20,000 – 31,500	8.1 – 14.6	0.22 – 0.39	2.1	27,200	11.0
Clear	3 - 5	24,000 – 39,500	5.6 – 12.5	0.21 – 0.34	1.8	29,500	8.2
Mud	3 - 5	14,500 – 29,000	5.4 – 11.7	0.20 – 0.28	2.2	25,400	7.6
367	6.5 - 8	11,000 – 16,500	10.5 –29.5	0.15 – 0.22	3.5	14,600	18.3
403A	7 - 8	13,500 – 18,500	16.5 – 23.2	0.18 – 0.28	3.5	16,500	19.4
403B	7 - 8	18,000 – 25,000	17.9 – 25.0	0.19 – 0.26	3.3	21,500	22.1

BA/ha = basal area measured in m^2 per hectare; Pre-trt seasonal transm. = transmittance prior to opening creation; DBH = diameter at breast height (1.3 m)

There is a significant relationship between linearalized (logarithmic transformed) post-treatment transmittance and SVF, at 1m heights measured at plot center when all plots were combined for Slave Lake and Fort St. John locations (R^2=0.56; p <0.0001; n=108). With the addition of pre-treatment light transmittance of each individual plot, this relationship is significantly improved (R^2=0.735) (Figure 2.10). This is likely because pre-treatment light levels were highly variable between each of the six randomly selected plot locations in a given stand (Table 2.3a and 2.3b). Pre-treatment light levels were strongly correlated to post-treatment levels independent of SVF.

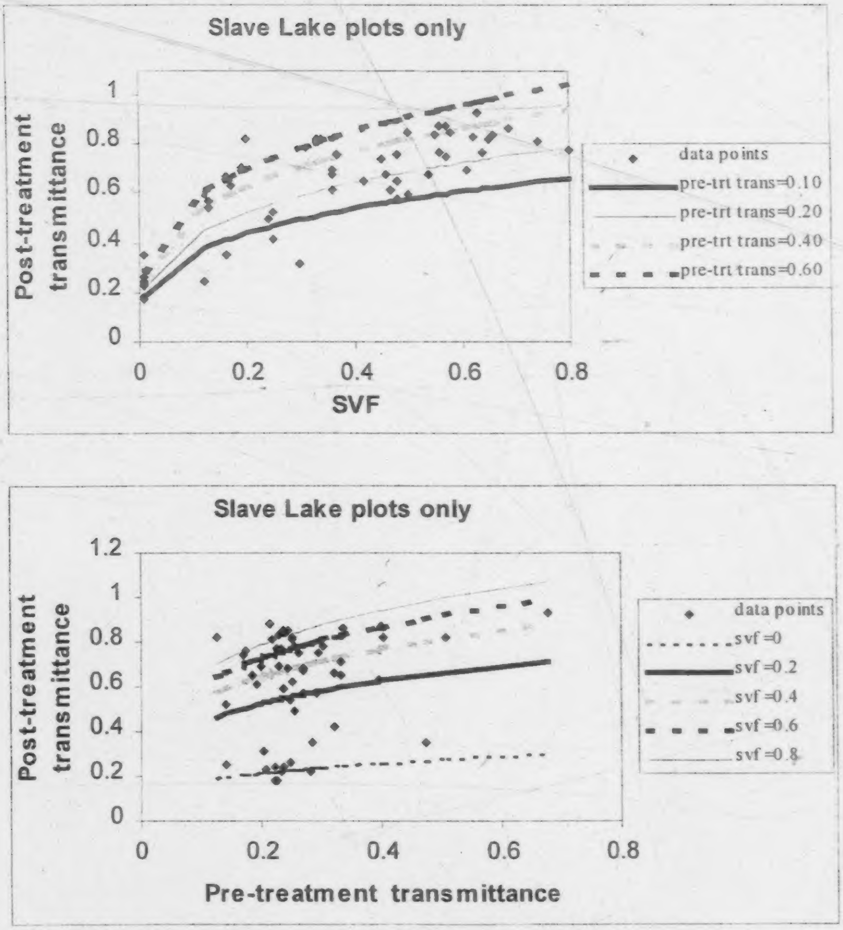


Figure 2.8. Scatterplot showing relationship between post treatment transmittance and sky view factor (SVF) and pre treatment transmittance for Slave Lake plots only. The lines are described by the equation: Ln(post-trt transmittance) = 0.23607 + 0.294046 Ln (SVF) + 0.254233 Ln (pre-trt transmittance); $R^2 = 0.8231$, RMSE = 0.206, n=54.

Relationships between post-treatment transmittance and SVF and pre-treatment transmittance were developed individually for Slave Lake and Fort St. John stands. The higher coefficient of determination is seen in the Slave Lake stands (R^2=0.823) with less of the variation being explained by the proposed relationship for the Fort St. John stands (R^2=0.717) (Figures 2.8 and 2.9). The lower R^2 value obtained with the Fort St. John stands may be partially explained by the inclusion of the LTSPS blocks, which were perhaps too short and had not achieved crown closure, resulting in substantial variability in SVF and in light transmittance at this site. In order to test whether the three height groups in Slave Lake (2 –3.3 m; 3.5 – 5 m; and 7 –8 m) and the three height groups in Fort St. John (1.8 – 3 m; 3.5 –5 m; and 6.5 –8 m) could be combined for their respective location, extra sums of squares tests (Ott 1997, Ramsey and Schafer 1997) were carried out. For the Slave Lake blocks and the Fort St. John blocks the tests show that the coefficients for individual heights of stands are not significantly different (p=0.3375 and p= 0.501 respectively) and that data from stands of the different height groups can be combined in both cases. Testing of whether the two locations can be combined also shows that the coefficients are not significantly different (p=0.6044) and consequently all plots and all stand heights can be combined (Figure 2.10). Interpretation of all of the regression equations described here should be done with care in order to restrict extrapolation of the relationship beyond the limits of the individual variables sampled.

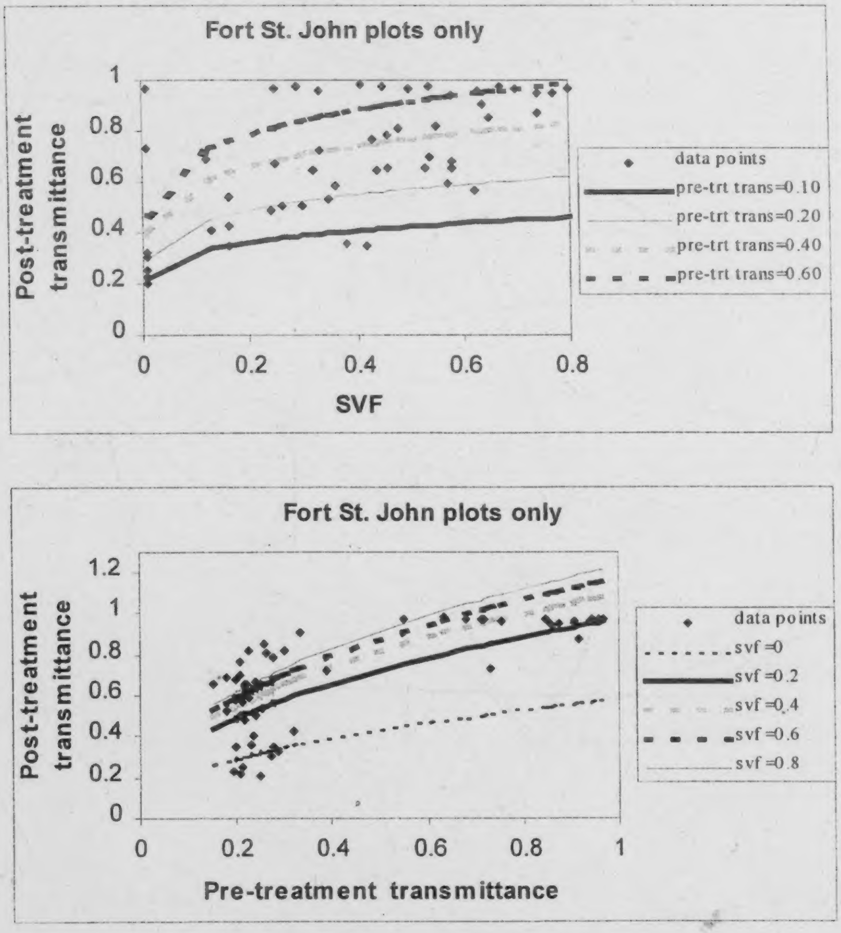


Figure 2.9. Scatterplot showing relationship between post treatment transmittance and sky view factor (SVF) and pre treatment transmittance for Ft. St. John plots only. The lines are described by the equation: Ln(post-trt transmittance) = 0.245799 + 0.169665 Ln (SVF) + 0.428911 Ln (pre-trt transmittance); $R^2 = 0.7168$, RMSE = 0.241, n=54.

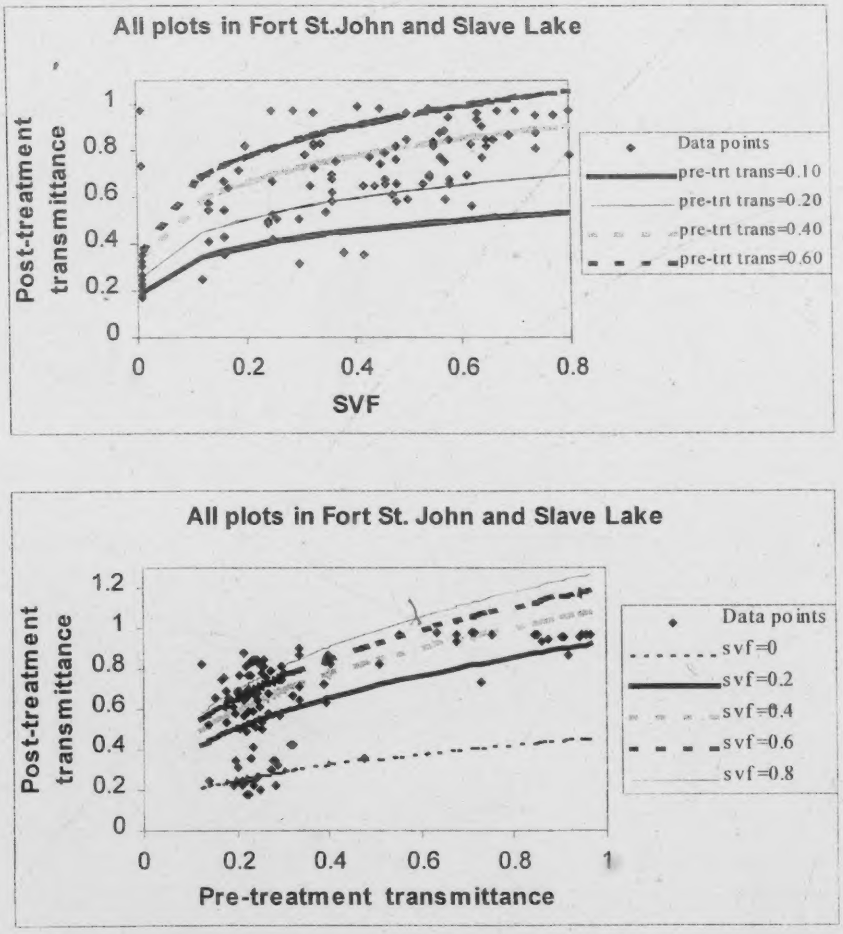


Figure 2.10. Scatterplot showing relationship between post treatment transmittance and sky view factor (SVF) and pre treatment transmittance for Slave Lake & Ft. St. John plots. The lines are described by the equation: Ln(post-trt transmittance) = 0.299779 + 0.231178 Ln (SVF) + 0.381009 Ln (pre-trt transmittance); $R^2 = 0.7354$, RMSE = 0.241, n=108.

The relationship between post-treatment transmittance and SVF and pre-treatment transmittance, as shown in Figure 2.10, illustrates that for a pre-treatment transmittance of 0.2 and a created opening with a SVF of 0.3, you will achieve a post-treatment transmittance level of 0.55; and, with a pre-treatment transmittance of 0.4 and a 0.5 SVF opening (where diameter of the opening is two times the stand height), you will achieve a post-treatment transmittance of 0.81 (Table 2.4). This relationship tends to over-predict post-treatment transmittance when the openings become large or when pre-treatment transmittance levels are high (Figure 2.10).

Table 2.4. A summary of estimates of transmittance levels in relation to pre-treatment transmittance and SVF created by openings of different sizes.

Pre-treatment transmittance	SVF	Predicted post-treatment transmittance
0.10	0.1	0.35
0.10	0.2	0.39
0.10	0.3	0.43
0.10	0.5	0.48
0.10	0.6	0.50
0.20	0.1	0.42
0.20	0.2	0.50
0.20	0.3	0.55
0.20	0.5	0.63
0.20	0.6	0.65
0.40	0.1	0.55
0.40	0.2	0.65
0.40	0.3	0.72
0.40	0.5	0.81
0.40	0.6	0.85
0.60	0.1	0.68
0.60	0.2	0.77
0.60	0.3	0.84
0.60	0.5	0.95
0.60	0.6	0.98

2.3.2 Vertical gradients of light levels

All stands near Slave Lake and stands in the two taller height classes near Fort St. John, show significant multi-linear relationships between post-treatment extinction (1 – DIFN) and vertical light levels in relation to measurement height (Table 2.5). The Fort St. John 2-3 m tall stands do not show significant relationships ($\alpha = 0.05$) between post-treatment extinction values and any of the independent variables tested. This is, again, most likely because these stands were too short and the stand densities too low and variable which lead to post-treatment light levels that were already very high at 1 m (regardless of the size of opening created) and the 2 m readings were, therefore, not very different. These stands were not used in the final analysis of light profile measurements.

For the remaining five groups, three models can be described which show similar trends in R^2 values and significance of individual coefficients (Table 2.5). In order to test whether the three height groups in Slave Lake (2 - 3.3 m; 3.5 - 5 m; and 7 - 8 m) and the two remaining height groups in Fort St. John (3 - 5 m; and 6.5 - 8 m) could be combined for their respective locations, extra sums of squares tests were carried out. For models 2 and 3, none of the 5 separate groups can be combined as the relationships yield significantly different coefficients. Extra sums of squares testing of model one (utilizing an $\alpha=0.05$), which describes a relationship between post-treatment extinction and relative height of measurement and SVF at the measurement position, indicates that combination of all three height groups near Slave Lake would not be statistically valid ($p=0.0021$) but combining of data from the two taller height classes is valid ($p=0.1338$). For the Fort St. John blocks, the tests show that the coefficients for individual heights of stands are not significantly different ($p= 0.641$) and that data from stands of the these two height groups can be combined. Testing to see whether data from the two taller height classes from the two locations could be combined showed that this would not be statistically valid ($p<0.0001$). Relative height is calculated as: measurement height divided by the average stand height.

Table 2.5. Model fit and significance of individual coefficients for three multiple linear regression models describing vertical light transmittance in relation to measurement height

	SL	SL	SL	FSJ	FSJ	FSJ
	2-3.3 m	3.5-5 m	7-8 m	2-3 m	3.5-5 m	6-8 m
1. LnPstExt=LnRelHt+LnSVF@measHt						
Model R^2	0.74	0.53	0.66	0.04	0.59	0.64
Prob > | T | Intercept	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Prob > | T | LnRelHt	0.0017	0.0002	<0.0001	0.6719	<0.0001	<0.0001
Prob > | T | LnSVF@measHt	<0.0001	<0.0001	<0.0001	0.2535	<0.0001	<0.0001
2. LnPstExt=LnRelHt+LnTrans@1m						
Model R^2	0.76	0.62	0.70	0.12	0.69	0.52
Prob > | T | Intercept	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Prob > | T | LnRelHt	0.0305	<0.0001	<0.0001	0.2001	<0.0001	<0.0001
Prob > | T | LnTrans@1m	<0.0001	<0.0001	<0.0001	0.4886	<0.0001	0.0016
3. LnPstExt=LnRelHt+LnSVF@1m						
Model R^2	0.74	0.52	0.66	0.09	0.55	0.59
Prob > | T | Intercept	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Prob > | T | LnRelHt	0.0320	0.0003	<0.0001	0.2401	<0.0001	<0.0001
Prob > | T | LnSVF@1m	<0.0001	<0.0001	<0.0001	0.8442	<0.0001	<0.0001

LnPstExt = natural log of post-treatment extinction; LnRelHt = natural log of the relative height of the measurement with respect to the average height of the surrounding stand; LnSVF@measHt = natural log of the SVF at each measurement height; LnTrans @ 1m = natural log of the post-treatment transmittance at a 1 m reference height; LnSVF@1m = natural log of SVF at 1m; SL=Slave Lake; and FSJ=Fort St. John.

The vertical light profile within the openings created in 2 –8 m stands near Slave Lake and in 3.5-8 m stands near Fort St. John, can be explained by the relationship between post-treatment extinction (1 – DIFN) and light levels relative to the measurement height within a circular opening. Models 2 and 3 (Table 2.5) show similar relationships because there is a significant correlation between the measurements of SVF at 1m and transmittance at 1m (R = 0.698), with transmittance at 1 m being generally higher for larger openings. Because of the ability to develop a common model for the two larger height classes in both locations, only the models that use SVF at measurement height will be used in the discussion of vertical light profiles.

Examination of the minimum SVF at measurement height for each of the 3 models (Figures 2.11 – 2.13) indicates that the proportion of available light that is blocked by overhead vegetation at a relative height of 0.5 (Table 2.6) is fairly consistent for the Slave Lake stands (<0.60 – <0.67) but the proportion is significantly less for the 3.5 – 8 m tall stands near Fort St. John (<0.36). For the Fort St. John stands extinction decreases at a much faster rate with decreasing relative height (Figure 2.13) than either of the two models for stands near Slave Lake.

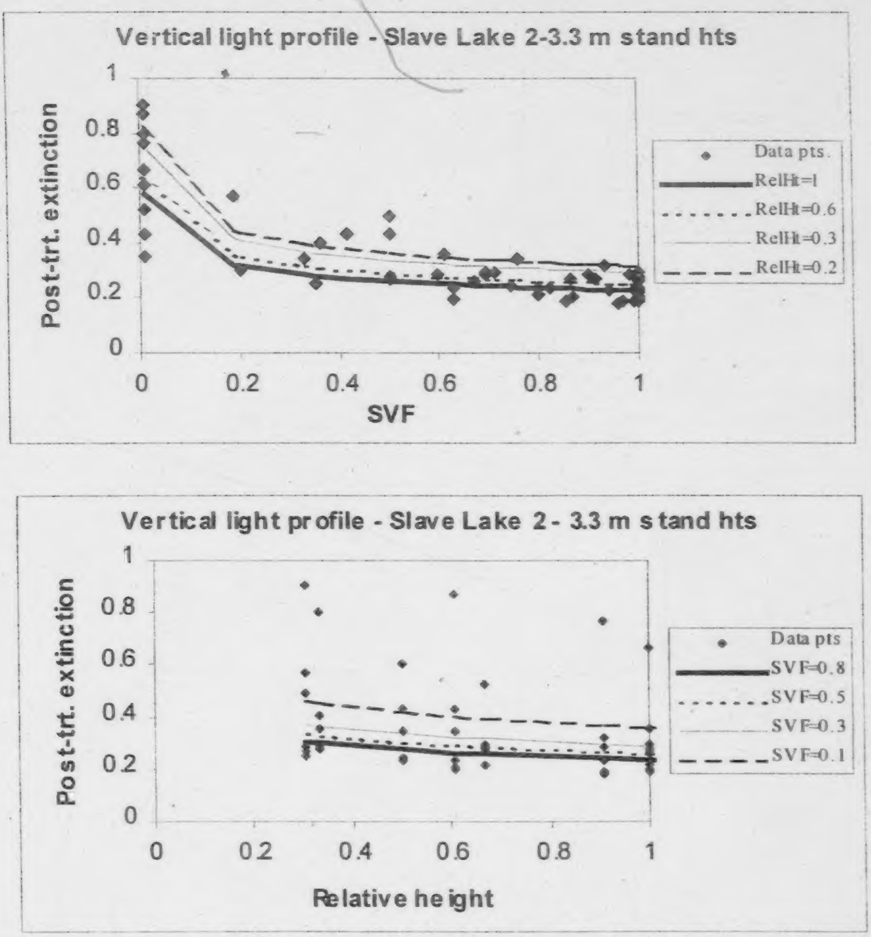
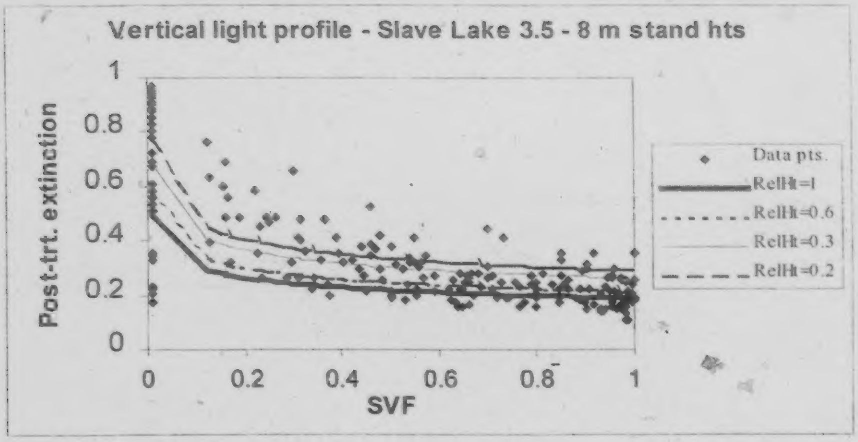


Figure 2.11. Scatterplot showing relationship between post treatment light extinction (1-transmittance) and SVF at successive 1m heights from ground level and relative height (measurement position with respect to the average height of surrounding stand) for Slave Lake 2- 3.3 m stands. The lines are described by the equation: Ln(post-trt extinction) = -1.4883 - 0.2135*Ln(RelHt) - 0.2040* Ln(SVF); $R^2 = 0.7441$, RMSE = 0.219, n=54.



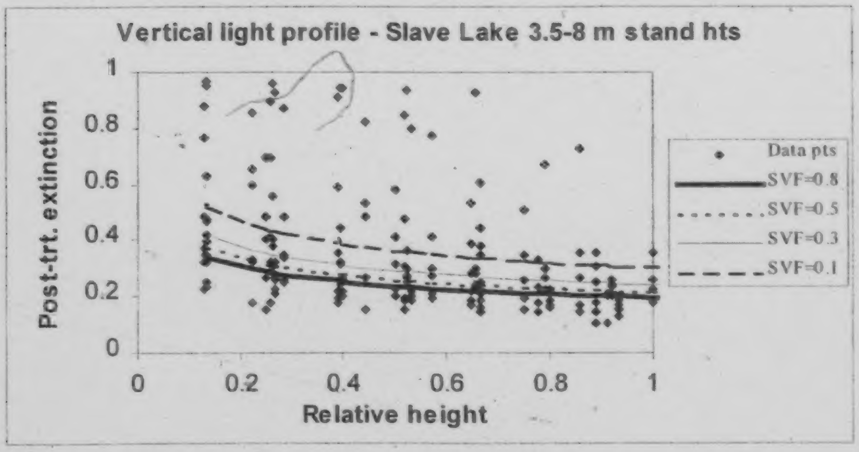


Figure 2.12. Scatterplot showing relationship between post treatment light extinction (1-transmittance) and SVF at successive 1m heights from ground level and relative height (measurement position with respect to the average height of surrounding stand) for Slave Lake 3.5 - 8 m stands. The lines are described by the equation: Ln(post-trt extinction) = -1.6739 - 0.2741*Ln(RelHt) - 0.2084* Ln(SVF); R^2= 0.6054, RMSE = 0.327, n=204.

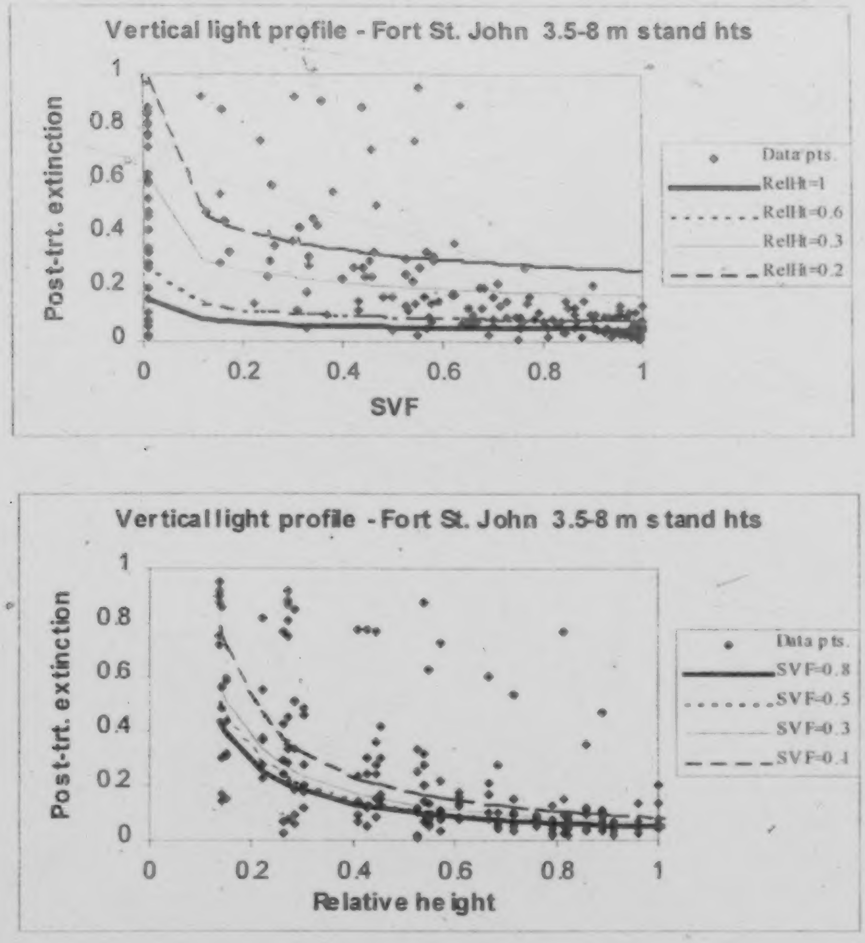


Figure 2.13. Scatterplot showing relationship between post treatment light extinction (1-transmittance) and SVF at successive 1m heights from ground level and relative height (measurement position with respect to the average height of surrounding stand) for Fort St. John 3.5 - 8 m stands. The lines are described by the equation: Ln(post-trt extinction) = -3.1114 -1.1148*Ln(RelHt) - 0.2805* Ln(SVF); R^2= 0.6155, RMSE = 0.703, n=204.

Data points that are shown in Figures 2.11 to 2.13 that are above the main body of points could be the result of potential measurement errors. No data points were excluded from this data analysis.

Table 2.6. Maximum proportion of available light blocked by overhead vegetation as predicted by 3 models

	SL 2 – 3.3 m	SL 3.5 – 8 m	FSJ 3.5 – 8 m
Min SVF@ measHt/Min RelHt	0/0.303	0/0.12	0/0.14
@ Relht=0.5[a]	<0.67	<0.60	<0.36
@ Relht=0.7[a]	<0.63	<0.54	<0.25
@ Relht=1.0[a]	<0.58	<0.49	<0.17
@ 0.9 SVF@measHt[b]	<0.30	<0.34	<0.43
@ 0.5 SVF@measHt[b]	<0.34	<0.38	<0.50
@ 0.3 SVF@measHt[b]	<0.38	<0.43	<0.58

[a] assumes the use of the minimum SVF at measurement height (i.e., no circular opening created)

[b] assumes the use of the lowest relative height measurement for treated openings

For stands that are between 2 and 3.3 meters tall near Slave Lake, at a relative height of 0.7, less than 0.63 of the light is blocked by overhead vegetation even at the lowest SVF at measurement height values (Figure 2.11, Table 2.6). The two taller height classes near Slave Lake show a slightly lower amount (<0.54) of light being blocked at this same relative height and the Fort St. John 3.5 to 8 meter stands blocked significantly less light (<0.25)(Table 2.6). Looking at large SVF at measurement height (0.9), for similar minimum relative heights (Slave Lake 3.5-8m and Fort St. John 3.5-8 m), the Slave Lake stands block less light than the Fort St. John stands (<0.34 and <0.43 respectively). For smaller views (0.3), the difference is even greater with the Slave Lake stands blocking <0.43 and the Fort St. John stands <0.58 (Table 2.6)

At a relative height of 0.5, stands in all three height classes near Slave Lake are at much lower light levels than stands that are 3.5 to 8 meters tall near Fort St. John – regardless of SVF (Table 2.7). Available light blocked by 2 to 3.3 meter stands near Slave Lake is slightly higher than the 3.5 to 8 meter stands in the same area but 3.5 to 8 meter stands near Fort St. John block significantly less light for all sky views (Table 2.7)

Table 2.7. Proportion of available light blocked for a relative height of 0.5 as predicted by 3 models

	SL 2-3.3 m	SL 3.5-8 m	FSJ 3.5-8 m
0.90 SVF@measHt	<0.27	<0.24	<0.10
0.50 SVF@measHt	<0.31	<0.27	<0.12
0.20 SVF@measHt	<0.37	<0.32	<0.16

Table 2.8. Proportion of available light blocked for a relative height of 0.7 as predicted by 3 models

	SL 2-3.3 m	SL 3.5-8 m	FSJ 3.5-8 m
0.90 SVF@measHt	<0.25	<0.22	<0.07
0.50 SVF@measHt	<0.29	<0.24	<0.09
0.20 SVF@measHt	<0.34	<0.29	<0.11

Higher light levels were experienced near the tops of stands near Fort St. John than for any of the height classes near Slave Lake (Table 2.8). This may be because of differences in the distribution of leaf area within the crown of trees within these two locations.

2.3.3 Temperature

The average values of minimum daily soil temperatures (at 15 cm depth) showed little trend with increasing SVF (Table 2.9). The above ground probes show a decreasing minimum temperature trend with increasing SVF – although substantial variation was observed at both probe heights (Table 2.9).

Table 2.9. Average of minimum daily temperatures for the period May 29, 2002 through September 16, 2002 at the three different probe heights for various SVFs

Approximate SVF at height of probe	15 cm below ground level	20 cm above ground level	1 meter above ground level
0.1	7.3	3.2	–
0.2	7.4	3.8	5.6
0.3	6.9	–	3.3
0.4	7.0	3.0	–
0.5	8.0	2.9	4.0
0.6	–	–	2.7

Minimum air temperatures, measured during a week of cool night temperatures in early July, at both 20 cm and at 1 meter above ground level at the center of the created openings, were very similar with the 20 cm position showing a consistently lower minimum temperature (Figure 2.14). This is consistent with expected trends, as suggested by Oke (1987) and Stathers (1989), with overnight temperatures just above ground level being lower than positions further above the ground. The lack of an even larger difference between these two positions may be the result of a lack of an understory shrub or grass component to trap colder air close to the ground.

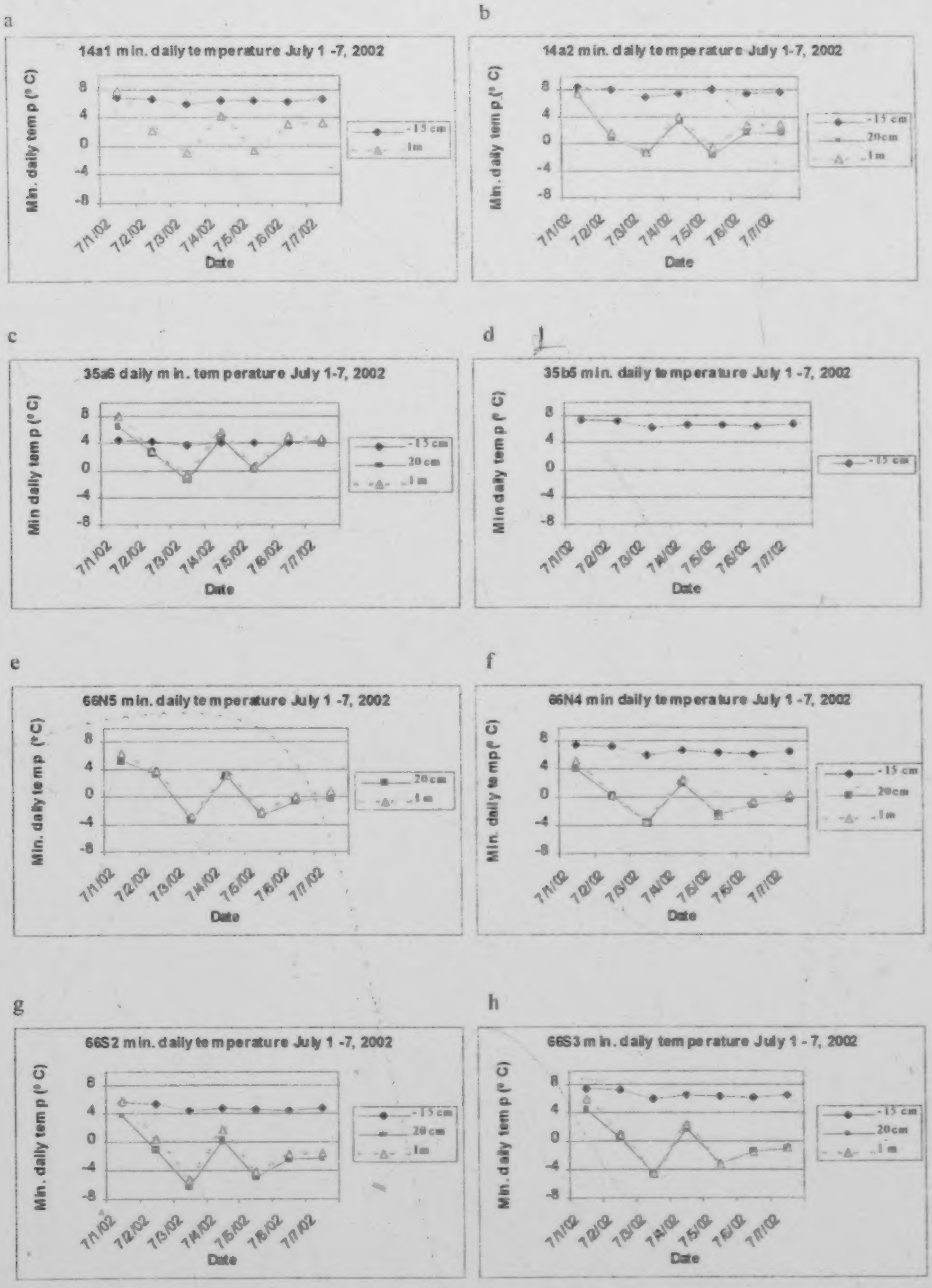


Figure 2.14 2.14a– 2.14h are examples of minimum daily temperature trends for temperature probes located at 15 cm below ground (n=13), 20 cm above ground (n=12) and 1 meter above ground level (n=12) for the period July 1 – 7, 2002. Probes that had more than 5% of total seasonal readings missing were not used in the analysis.

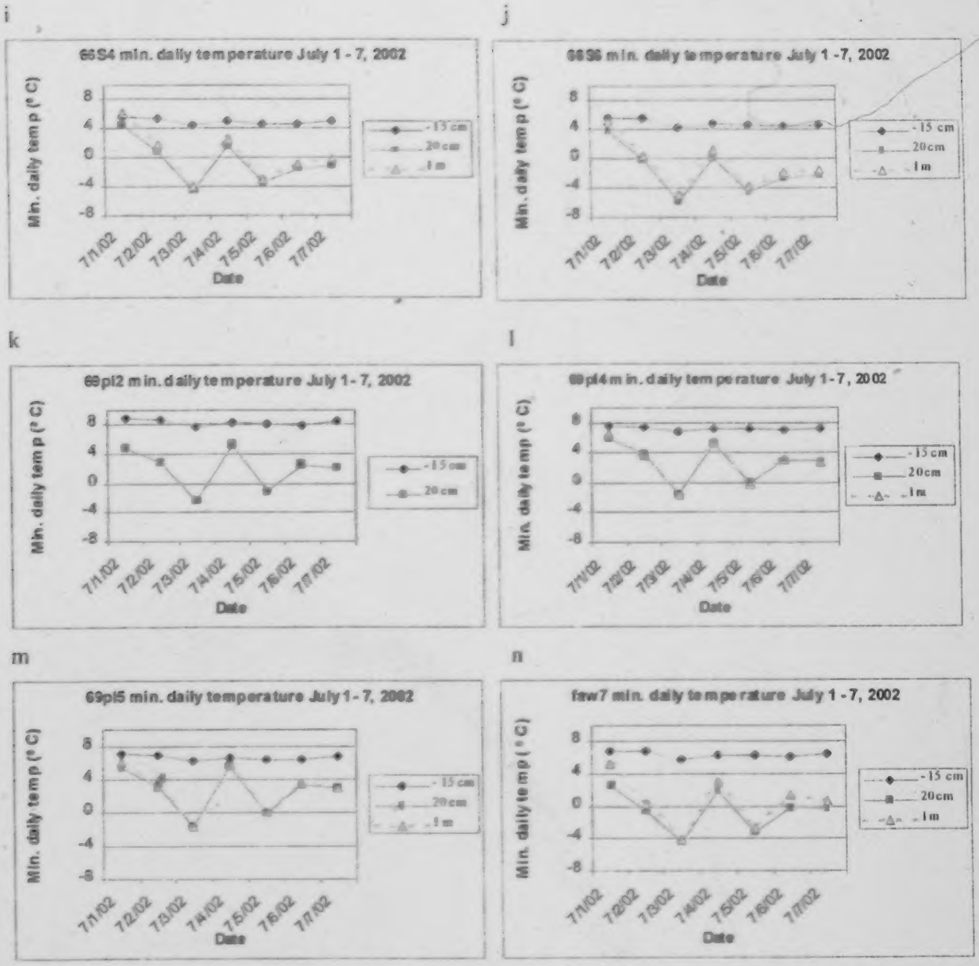
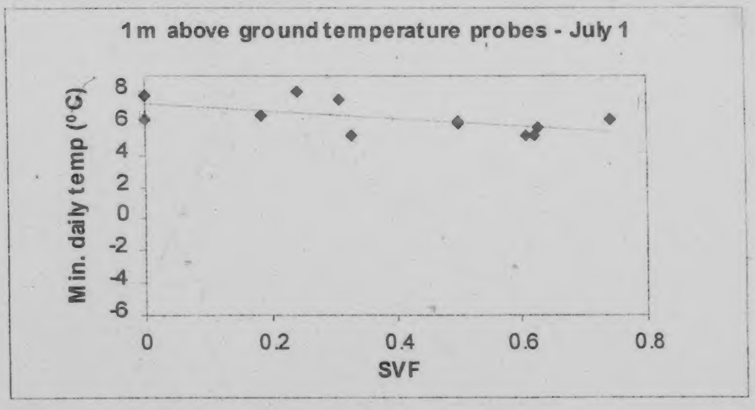


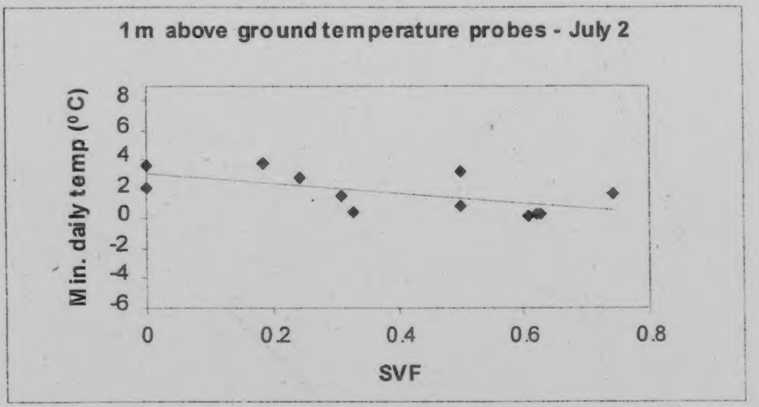
Figure 2.14 (continued) 2.14i – 2.14n are examples of minimum daily temperature trends for temperature probes located at 15 cm below ground (n=13), 20 cm above ground (n=12) and 1 meter above ground level (n=12) for the period July 1 – 7, 2002. Probes that had more than 5% of total seasonal readings missing were not used in the analysis.

The daily minimum temperature for specific days during the growing season can be predicted by SVF of created openings. On July 1, 2 and 3 for the 1 m temperature probe, there is a significant relationship between the minimum temperature and SVF, with minimum temperature decreasing with increasing SVF (Figure 2.15a- 2.15c). This relationship is not significant for all days tested independently throughout the growing season but is significant for this period that is leading up to a particularly cold day during the growing season (July 3, 2002) with temperatures decreasing from July 1-3 and then increasing again substantially from July 3–4 by about 7 ° C (Figure 2.14). July 1, 2 and 3 all show significant relationships and moderate R^2 values for regressions of minimum temperature against SVF while analysis of July 4th data gives a markedly lower significance and R^2 value ($p=0.185$, $R^2=0.168$).

2.15a



2.15b



2.15c

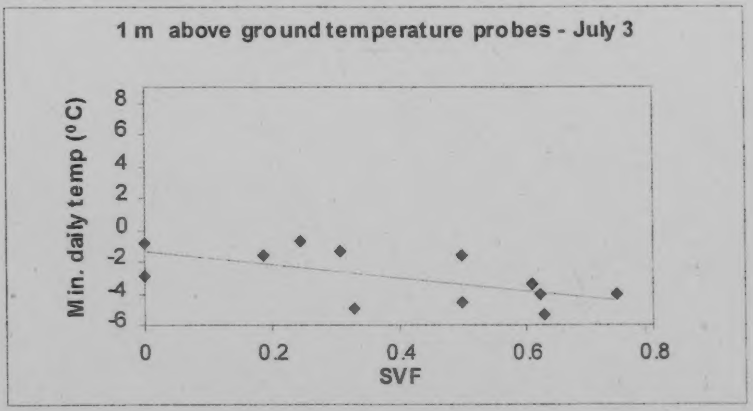


Figure 2.15. Relationship between the minimum daily temperature on July 1 -3, 2002 and SVF for the 1 meter above ground temperature probe as described by the following equations: July 1 min. temp = 7.233 – 2.36 *SVF; R^2=0.367; p=0.037; n=12, July 2 min. temp = 3.08 – 3.39 *SVF; R^2=0.400; p=0.027; n=12, and July 3 min. temp = -1.36 – 4.09 *SVF; R^2=0.373; p=0.035; n=12.

2.3.4 Frequency of frost and SVF

At the 1 meter probe height, the number of times that the hourly minimum temperature was below - 2°C increases with increasing SVF but the relationship is not statistically significant ($p=0.126$) and the R^2 value is low ($R^2=0.218$) (Figure 2.16) but the number of times decreases with increasing density of the surrounding stand ($R^2= 0.381$; $p=0.033$; Figure 2.17) and with increasing height of the surrounding stand ($R^2= 0.586$; $p=0.004$; Figure 2.18). The probes located at 20 cm above ground level show a similar trend (Table 2.10).

Table 2.10. Occurrences of cold temperatures varies by stand characteristics at different probe heights

Relationship between # of times min. hourly temp < -2°C **and:**	Probe height above ground	R^2	p-value	n
SVF	1 meter	0.218	0.126	12
surrounding stand density	1 meter	0.381	0.033	12
surrounding stand height	1 meter	0.586	0.004	12
SVF	20 cm	0.0033	0.859	12
surrounding stand density	20 cm	0.320	0.054	12
surrounding stand height	20 cm	0.570	0.005	12

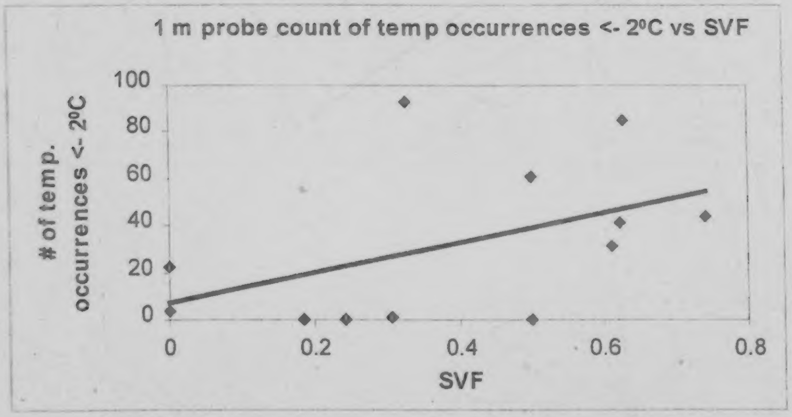


Figure 2.16. Relationship between the number of times that the min. hourly temperature was less than –2 ° C during the period May 29 – Sept. 16, 2002 and SVF (for the 1 m above ground temperature probe) as described by the equation: # of Occurrences < –2 ° C = 7.28 + 63.08*SVF; $R^2 = 0.218$; $p=0.126$; $n=12$.

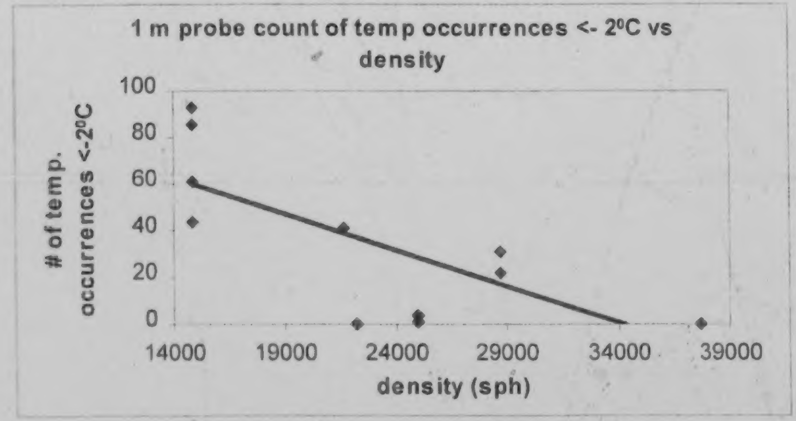


Figure 2.17. Relationship between the number of times that the min. hourly temperature was less than –2 ° C during the period May 29 – Sept. 16, 2002 and density of the surrounding stand (for the 1 m above ground temperature probe) as described by the equation: # of Occurrences < –2 ° C = 105.79 – 0.0031*density; $R^2 = 0.586$; $p=0.004$; $n=12$.

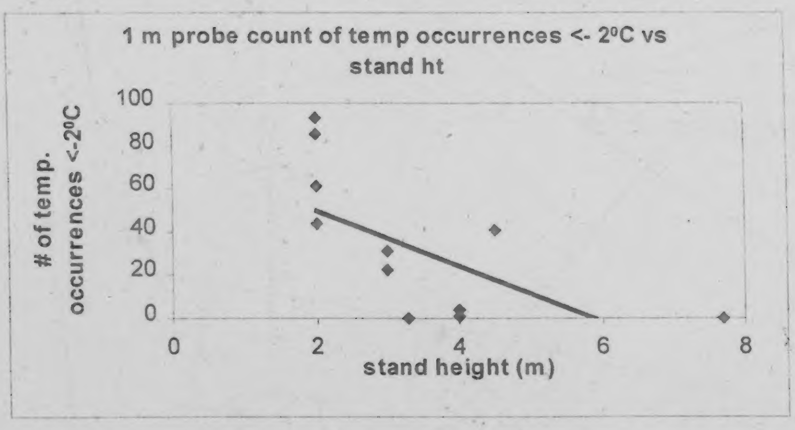


Figure 2.18. Relationship between the number of times that the min. hourly temperature was less than –2 ° C during the period May 29 – Sept. 16, 2002 and the surrounding stand height (for the 1 m above ground temperature probe) as described by the equation: # of Occurrences < –2 ° C = 75.74 – 12.91*stand ht; R^2 = 0.381; p=0.033; n=12.

A relationship that utilizes both the stand height and density gives a good overall indication of the influence of both the height and the density of the surrounding stand with respect to the of occurrences of colder temperatures (Figure 2.19).

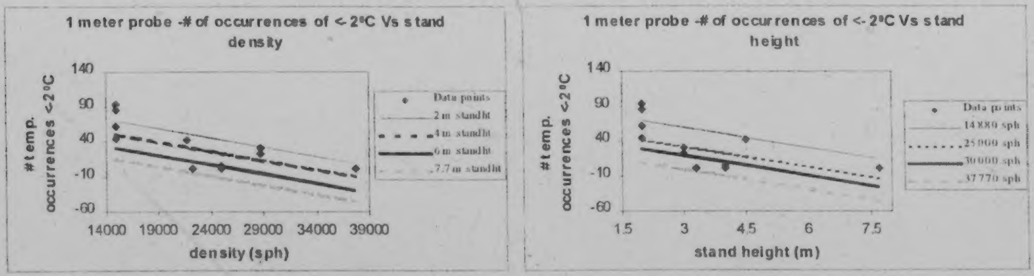


Figure 2.19. Scatterplot showing relationship between the number of times that the minimum hourly was less than -2° C during the period May 29 – Sept. 16, 2002 and and density of the surrounding stand and height of the surrounding stand at 1 m above ground. The lines are described by the equation: # of Occurrences < -2 ºC = 127.82 – 9.62*Standht - 0.00265*Density; R› = 0.7853, RMSE = 17.28, n=12.

There is a general increasing trend in standard deviation of the minimum temperature with increasing SVF for the probes at 1 meter, with an R^2 value of 0.45 and a p-value of 0.018 (Figure 2.20). This indicates that variation in temperature ranges increases with increasing SVF which agrees with work done by Carlson and Groot (1997) in 40 year old aspen stands. The trend does not hold for the 20 cm probes (Table 2.11) and this may be partially explained by the effect being moderated by vegetation regrowing and covering probes over the course of the growing season around the sensors at this height.

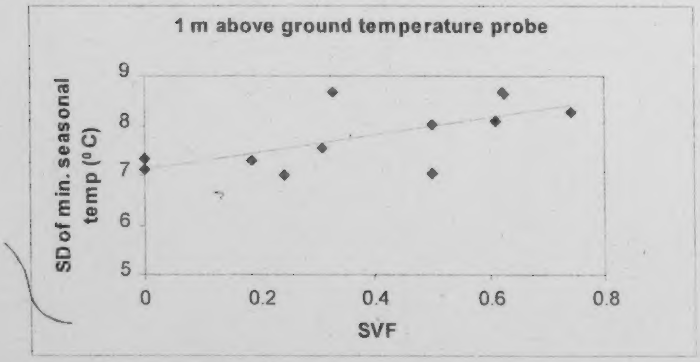


Figure 2.20. Relationship between the standard deviation of the seasonal minimum temperature and SVF for the 1 meter above ground probe as described by the equation: SD of min seasonal temp = 7.11 + 1.78 *SVF; R^2= 0.45; p=0.018; n=12.

Table 2.11. Relationship between standard deviation (SD) of minimum seasonal temperature and SVF

Probe height above ground	R^2	p-value	n
1 meter	0.450	0.018	12
20 cm	0.191	0.155	12

If the minimum temperature on a cold day in the growing season (July 3, 2002) is considered for the probes at 20 cm above ground level, there is a strong relationship between minimum temperature and the density and height of the surrounding stand. (R^2=

0.79) – regardless of the opening size (Figure 2.21). A similar relationship holds for the probes located at 1 meter above ground level (Table 2.12).

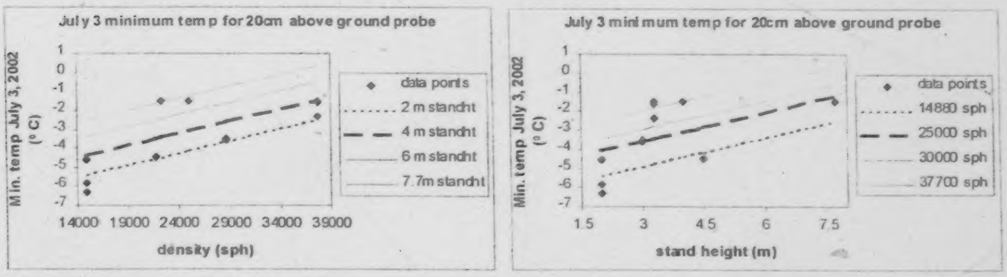


Figure 2.21. Scatterplot showing relationship between minimum temperature on a cold day in the growing season (July 3, 2002) and density of the surrounding stand and height of the surrounding stand) at 20cm above ground. The lines are described by the equation: Min. temperature (July 3) = -8.263 + 0.5008*Standht + 0.000126*Density; $R^2 = 0.7856$, RMSE = 0.892, n=12.

Table 2.12. Relationship between minimum July 3 temperature and surrounding stand density and height

Probe height above ground	R^2	Prob >|t| for surrounding stand ht	Prob >|t| for surrounding stand density	n
1 meter	0.749	0.0093	0.0129	12
20 cm	0.786	0.0171	0.0022	12

For the 20 cm probe height on this particularly cold day, if you considered an opening within a higher density stand (37,700 sph) that is 2 meters tall, you could expect a minimum temperature of -2.5°C, whereas an opening in a 7.7 meter tall stand of the same density would experience of minimum temperature of +0.3°C. Consideration of an opening in a moderate density stand (22,200 sph) that is 2 meters tall would yield a minimum temperature of -4.5°C whereas an opening in a 7.7 meter stand of this same density would experience a minimum temperature of -1.6°C. An opening in a lower density stand (14,880 sph) that is 2 meters tall would yield a minimum temperature of

-5.4°C whereas an opening in a 7.7 meter stand of this same density would experience a minimum temperature of -2.5°C.

2.3.5 Growing degree days

At 20 cm above ground level, the accumulated growing degree days (GDDs) show an increasing trend with increased SVF. This relationship is most significant and has the highest coefficient of determination near the beginning of the growing season (Figure 2.23). As the growing season progresses the relationship shows a similar trend although its strength decreases and by the end of the season it has become non-significant (Table 2.13).

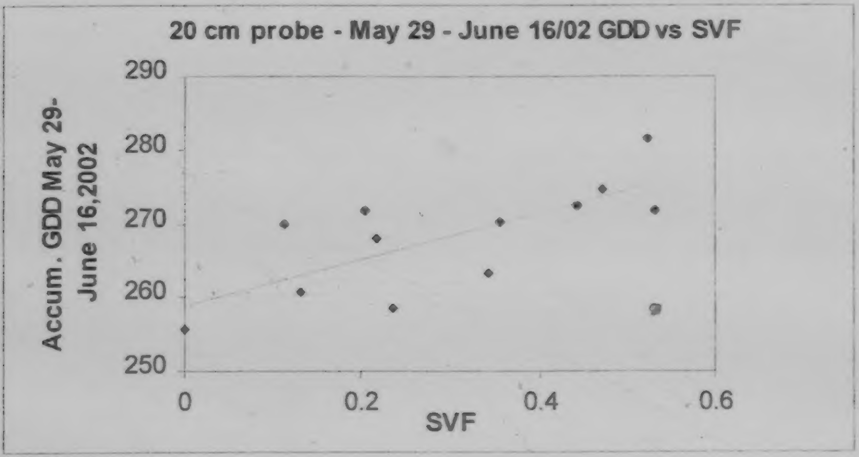


Figure 2.22. Scatterplot showing the relationship between the number of GDD accumulated prior to June 16, 2002 and SVF for temperature probes located at 20 above ground level in the stands near Slave Lake as described by the equation: accum GDD May 29 to June16 = 258.91 + 31.212*SVF; R^2=0.541, p=0.006, n=12.

Table 2.13. Changes in significance of relationship between GDD measured at 20 cm height and SVF with period of measurement

Accumulated GDD	*R^2*	*p-value*
GDD May 29 – June 16, 2002	0.541	0.0064
GDD May 29 – July 1, 2002	0.412	0.0245
GDD May 29 – July 16, 2002	0.514	0.0087
GDD May 29– August 1, 2002	0.532	0.0070
GDD May 29 – August 16, 2002	0.464	0.0147
GDD May 29 – September 1, 2002	0.390	0.0200
GDD May 29– September 17, 2002	0.310	0.060

GDD = growing degree days (based on the average of the daily temperature summed when the average temperature is greater than 5 ° C). Accumulated GDD is calculated based on successively increasing the measurement period by approximately two weeks until the entire period from May 29 – September 16, 2002 has been considered.

The only significant relationship for the probes located 15 cm below ground level was between minimum temperature on a cold day in the growing season (July 3,2002) and the density of the surrounding stand (R^2=0.495; p=0.0073 n=13) (Figure 2.23). There was no significant relationship though between minimum soil temperature and the height of the surrounding stand.

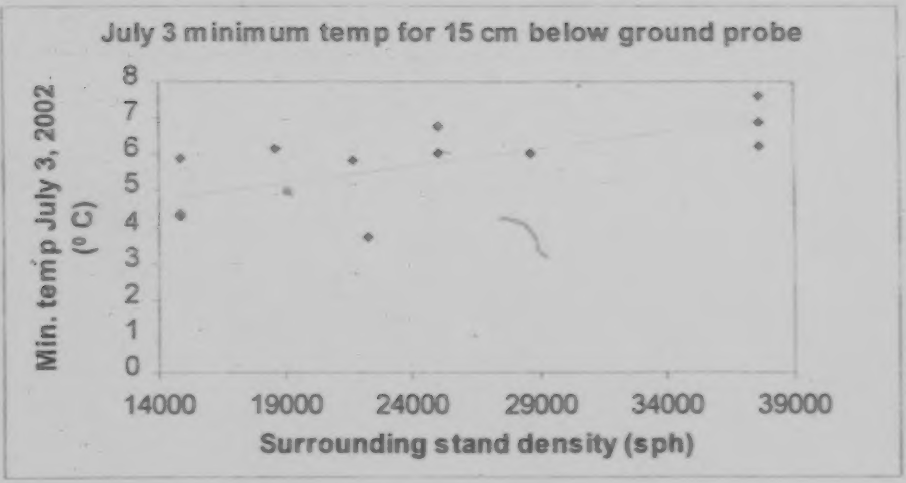


Figure 2.23. Scatterplot showing the relationship between the min. temperature on a cold day in the growing season (July 3, 2002) and density of the surrounding stand for Slave Lake at a probe height of 15 cm below ground as described by the equation: Min temp (July 3) = 3.485 + 0.0000915*density; $R^2=0.45$; $p=0.0073$; $n=13$

2.4 *Discussion*

Results from this study indicate that post-treatment light levels, at 1 meter above ground in the center of a circular opening, increase with increasing SVF and with light level present before openings are created. For a circular opening that is equal in radius and stand height (SVF=0.5), post-treatment transmittance levels increased to 0.48 from a pre-treatment level of 0.1 while post-treatment levels increased to 0.81 from a pre-treatment level of 0.4 (Table 2.4). For a circular opening that is one half the size in radius as apposed to stand height (SVF=0.2), post-treatment transmittance levels only increased to 0.39 from a pre-treatment level of 0.1 while post-treatment levels only increased to 0.65 from a pre-treatment level of 0.4 (Table 2.4).

Groot et al. (1997) found that circular openings in 19 meter tall aspen dominated stands in central Ontario with a SVF of 0.05 produced a transmittance value of 0.26 and a circular opening with a SVF of 0.18 produced a transmittance value of 0.55. An 18 meter east-west strip with a SVF of 0.43 produced a transmittance value of 0.68. These stands were quite open with a 0.18 transmittance for the intact forest. Canham et al. (1990) found that in a 27 meter old-growth northern hardwood stand in southwestern Ohio, transmittance values were 0.018 in openings with a SVF of 0.033 and 0.10 in openings with a SVF of 0.12. Intact forest in this location had very low initial transmittance levels of 0.003 to 0.038. Lieffers et al. (1999) show transmittance values of 0.3 for openings with a SVF of 0.2 and of 0.55 for openings with a SVF of 0.5 in a 10 meter tall birch stand. The intact forest in this location had a transmittance of 0.20.

Comparison of the transmittance predicted from this study (utilizing the intact forest transmittance values described in the Groot et al. (1997) study with the transmittance values found there shows that this relationship tends to predict slightly smaller post-treatment transmittance values except in the case of very small SVF (Figure 2.24). The difference here might be explained by the older age and size of these stands in Ontario – they had probably already gone through the 'competition bottleneck' and LAI would be declining in these stands. This is in contrast to the stands measured in this study and consequently transmittance values would be lower for these younger stands.

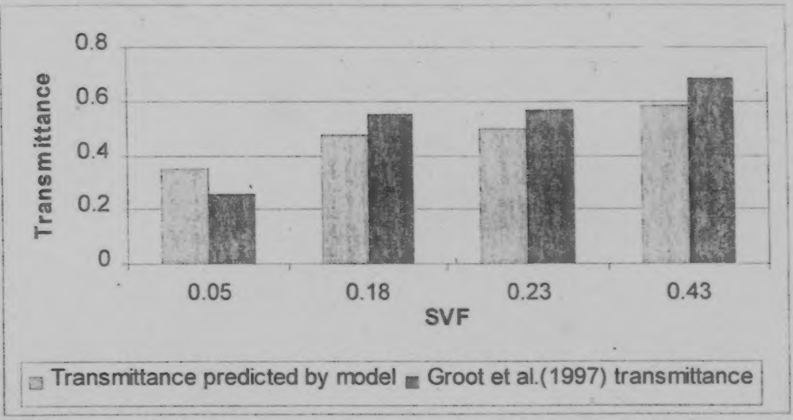


Figure 2.24. Comparison between post-treatment transmittance values predicted by the model described in Figure 2.10 holding the pre-treatment transmittance value constant at 0.18 (Groot et al. (1997) intact forest transmittance level) and transmittance levels measured by Groot et al. (1997). For SVF=0.43 the Groot et al. (1997) value is for a 18 m E-W strip not a circular opening.

The three different height groups in both locations did not yield coefficients that were significantly different from each other, indicating that stands from 2–8 meters in height in these mesic, moderate nutrient sites behaved in a similar manner. Likewise the two locations yielded similar coefficients. A common model can be utilized for all 3 height groupings in Slave Lake, Alberta and Fort St. John, British Columbia.

Even though light levels measured at 1m within openings did not show differing behavior between heights of stands or locations of stands, the vertical light profiles measured show significantly different coefficients between locations and between the shortest height class of stands near Slave Lake and the two taller classes in this location. This signifies that the stands near Slave Lake and stands near Fort St. John behave differently and separate models should be utilized. A separate model should also be utilized for the 2 to 3.3 meter stands near Slave Lake. A possible reason why the relationships suggested by the data in the shortest height group near Slave Lake and the combined 2 taller height groups may be that the relative amount of crown may change as the stands grow in height. Leaf area may be different for the stands located near Slave Lake as opposed to those located near Fort St. John and also between stands of different heights within each location (Lieffers et al. 2002). Actual calculation of leaf area index using LAI-2000 measurements show that on average for a given relative height within the stand that the amount of leaf area above that height is greater for the Slave Lake than the Fort St. John stands. Crown form with respect to branchiness may be different for stands of different heights and different locations. Some of these differences may be more apparent as you move vertically through an opening within a stand than for positions closer to ground level.

As you move vertically upward through 3.5 to 8 meter tall stands near Fort St. John, the amount of light that is blocked by surrounding and overtopping vegetation decreases more quickly than in stands of comparable height near Slave Lake. This may be a result of differences in the distribution of the leaf area within aspen in the two locations.

In 2 to 3.3 meter tall stands near Slave Lake there is little difference in post-treatment extinction levels regardless of relative height except for very small openings (SVF<0.2) (Figure 2.11). For small openings in 3.5 to 8 meter tall stands near Slave Lake, the level of light is less at a low relative height of 0.2 than near the top of the stand whereas in 2 to 3.3 meter tall stands the light level at a low relative height is very close to that near the top of the stand (Figures 2.11 and 2.12).

At a relative height of 0.5, there is a marked distinction between the difference between light levels in small and large openings and as you move upwards through the stand this distinction becomes less (Table 2.14). The Fort St. John 3.5 to 8 meter tall stands have the lowest overall difference between light levels in small and large openings and the difference also decreases at a faster rate as you move upwards through the stand (Table 2.14).

Table 2.14. Difference in light extinction level between sky view exposed when no opening is made and that exposed when SVF=0.5 for various positions of relative height

Stand description	RelHt=0.5	RelHt=0.7	RelHt=0.9
SL 2 – 3.3 m	0.37	0.34	0.32
SL 3.5 – 8 m	0.33	0.30	0.28
FSJ 3.5 – 8 m	0.23	0.16	0.12

The vertical light profile data that has been described here can be used to represent light levels that may be experienced after openings have been created. Relative height could represent the height of a white spruce in an opening compared to the height of the stand overstory. In areas similar to those found near Slave Lake in a 2-3.3 m tall stand where a light transmittance value of 0.6 of full sunlight was desired and the height of a spruce sapling was 0.3 times the height of the surrounding stand, a SVF of 0.213 would be required. For stands that are 3 meters tall this SVF would correspond to a diameter of 3.12 meters. For 3.5 to 8 meter tall stands such as those near Slave Lake where a light transmittance value of 0.5 was desired and the height of a spruce sapling was 0.2 times the height of the surrounding stand, a SVF of 0.075 would be required. A 2.85 meter diameter opening would be required to achieve this SVF in a 5 meter tall stand. The same criteria in 3.5 to 8 meter tall stands such as those near Fort St. John would require an opening with a SVF of 0.11 and an opening diameter of 3.53 meters.

Radiative frosts occur most commonly within openings during calm clear nights. This is because the exposed night sky is much colder than the vegetative surface and there is a net loss of long-wave radiation to the atmosphere. The larger the opening the more cold atmosphere is exposed. Under cloudy conditions the atmosphere is relatively warmer and with small gaps in a forest canopy there is less exposure to the cold atmosphere and the surrounding canopy helps modify the temperature environment making frost less likely to occur. In early summer temperatures less than -4°C or -5°C are more likely to cause irreversible frost injury to young trees (DeLucia and Smith 1987) especially in young foliage. In gaps on calm, clear nights during the growing season, there is not only an increased chance of radiative frost; there is also an increased chance of high light levels the following day. Frost damage has been found to be significantly worse when followed by periods of high light (Lundmark and Hällgren 1987; Örlander 1993; Gillies and Binder 1996; Langvall and Örlander 2001).

For stands less than 8 meters tall near Slave Lake the expected relationship between minimum temperatures and SVF, as described by Groot and Carlson (1996) for 19 meter tall aspen stands located in Central Ontario, does not hold. This may be because there was a large variation between the density and height of the stands surrounding the created openings or it may be that the relationship just does not hold in younger stands in the western boreal. For this project, stands were chosen to cover the range of SVFs that had been created but because minimum temperatures on cold days during the growing season were more affected by the height and density of the surrounding stands than by the size (relative to stand height) of the opening, the effect of opening is lost in this variation. In order to better determine the effect of SVF on the minimum temperature levels, sampling may need to be standardized across levels of density and height of the surrounding stands. Temperature probes were also set up in the center of openings and over the measurement period there was some re-growth of vegetation within the openings, with the rate of re-growth not always being consistent between openings. This is likely the cause of some of the variation experienced between probes (especially for the 20 cm above ground level probes which would have been more directly affected). The 2002 growing season also experienced less than an average number of occurrences of temperatures under -2˚C because of more overcast conditions during large parts of the growing season. The temperatures detected over the 2002 growing season are unlikely to cause significant frost injury to young trees growing within gaps but the relationships developed here do indicate that larger openings do experience colder overnight temperature as do less dense and shorter stands.

The likelihood of increased frost occurrences appears greater in shorter and less dense stands. On particularly cold days during the growing season there is an increased likelihood of cold temperatures with increasing SVF for probes located at 1 meter above ground level. This relationship is not significant for the 20 cm above ground probes, which may be because of the effects of vegetation re-growth affecting the variation of these samples.

This study looked at only mesic, medium nutrient sites within two areas of the western boreal forest. Further study would be necessary to determine if a common relationship holds on either wetter or drier sites or at sites at different elevations or geographic locations. Future research could include studies looking at the differences in morphological characteristics of trees during the first 30 years of development to perhaps better answer the question of the differences in vertical light gradients between shorter and taller stands near Slave Lake and between the two locations. Research into canopy gap closure rates in mixedwood stands in the western Canadian boreal forest would also be beneficial. A more in depth look at how temperatures are affected by size of gap that stratifies openings within various levels of stand density and height would answer some of the questions brought up here about whether the occurrence of low temperatures increases with opening size holds within stands younger than 30 years . Care should be taken to ensure shrub and herb layers are kept continuously clipped throughout the growing season

2.5 Conclusions

For stands with a pre-treatment transmittance at 1 m of 0.1, an opening with a SVF of 0.6 (diameter of opening that is 2.45 times the stand height) or larger, would be needed to produce light levels of 0.5. For stands with a pre-treatment transmittance at 1 m of 0.2, an opening with a SVF of 0.2 (diameter of opening that is equal to the stand height) would be needed to produce light levels of 0.5. For stands with a pre-treatment transmittance at 1 m of 0.4, an opening with a SVF of 0.1 (diameter of opening that is one half the stand height) would be needed to produce light levels of 0.5. The rate of change for the decrease in light extinction varies with the height of stand sampled as well as with the location of the stand. Temperatures are more likely to create growing season frost problems when openings are created within stands that are shorter and have lower densities. Results suggest that there is an increasing chance of frost on particularly cold days within the growing season with increasing SVF at a 1 m above ground height as indicated by previously published studies. This study also showed that temperature fluctuations also increase with increasing sky view factor. However, though stand density and height had a significant effect on the frequency of cold temperature, sky view factor was not significantly correlated with frequency.

2.6 References

Awada, T.,and Redmann, R.E. 2000. Acclimation to light in planted and naturally regenerated population of white spruce seedlings. Can. J. Bot. Vol. 78: 1495-1504.

Beckingham, J.D., and Archibald, J.H. 1996. Field guide to ecosites of northern Alberta. Can. For. Ser. Special Report 5. 412 pp.

Bigras, F.J., and Hébert, C. 1996. Freezing temperatures and exposure times during bud break and shoot elongation influence survival and growth of containerized black spruce (*Picea mariana*) seedlings. Can. J. For. Res. 26: 1481-1489.

Canham, C., Denslow, J.S., Platt, W.J., Runkle, J.R., Spies, T.A., and White, P.S. 1990. Light regimes beneath closed canopies and tree-fall gaps in temperate and tropical forests. Can. J. For. Res. 20: 620- 631.

Cannell, M.G.R., and Grace, J. 1993. Competition for light: detection, measurement and quantification. Can. J. For. Res. 23: 1969-1979.

Carlson, D.W., and Groot, A. 1997. Microclimate of clear-cut, forest interiors, and small openings in trembling aspen forest. Agric. For. Meterology. 87: 313-329.

Chen, H.Y.H. 1997. Interspecific responses of planted seedlings to light availability in interior British Columbia: survival, growth, allometric patterns, and specific leaf area. Can. J. For. Res. 27: 1383-1393.

Coates, K.D. 2002. Tree recruitment in gaps of various size, clearcuts and undisturbed mixed forest of interior British Columbia, Canada. For. Ecol. Man. 155: 387-398.

Coates, K.D., and Burton, P.J. 1999. Growth of planted tree seedlings in response to ambient light levels in northwestern interior cedar-hemlock forests of British Columbia. Can. J. For. Res. 29: 1374-1382.

Cochran, P.H., and Berntsen, C.M. 1973. Tolerance of lodgepole and ponderosa pine seedlings to low night temperatures. Forest Sci. 19: 272-280.

Comeau, P.G. 1996. Why mixedwoods? In silviculture of temperate & boreal broadleaf conifer mixtures. Land Management Handbook #36. BC Ministry of Forests-Research Branch.

Comeau, P.G. 2000. Measuring Light in the forest. Extension Note #42 BC Ministry of Forests Research Branch.

Comeau, P.G., Braumandl, T.F., and Xie, C. 1993. Effects of overtopping vegetation on light availability and growth of Englemann spruce (*Picea engelmannii*) seedlings. Can. J. For. Res. 23: 2044-2048.

Comeau, P.G., Gendron, F., and Letchford, T. 1998. A comparison of several methods for estimating light under a paper birch mixedwood stand. Can. J. For. Res. 28: 1843-1850

Comeau, P.G., Macdonald, R., Bryce, R. 2002. SLIM Version 2.1i (Spot Light Interception Model). B.C. MOF.

Constabel, A.J., and Lieffers, V.J. 1996. Seasonal patterns of light transmission through boreal mixedwood canopies. Can. J. For. Res. 26: 1008-1014.

David, A.J., Zasada, J.C., Gilmore, D.W., and Landhäusser, S.M. 2001. Current trends in the management of aspen and mixed aspen forests for sustainable production. For. Chron. 77(3): 525-532.

Delucia, E.H., and Smith, W.K. 1987. Air and soil temperature limitations on photosynthesis in Englemann spruce during summer. Can. J, For. Res. 17: 527-533.

FitzGerald, R.D., and Hoddinott, J. 1983. The utilization of carbohydrates in aspen roots following partial or complete top removal. Can. J. For. Res. 13: 685-689.

Geiger, R. 1965. The climate near the ground. Harvard University Press Cambridge, Massachusetts. 609 pp.

Gendron, F.,Messier, C., and Comeau, P.G. 1998. Comparison of different methods for estimating light transmittance in forests. Agric. For. Met. 92: 55-70.

Gillies, S.L., and Binder, W.D. 1996. The effect of sub-zero temperatures in the light and dark on cold-hardened, dehardened and newly flushed white spruce (Picea glauca,{Moench.] Voss) seedlings. New For. 13: 91-104.

Greene, D.F., Zasada, J. C., Sirois, L., Kneeshaw, D., Morin, H., Charron, I., and Simard, M.-J. 1999. A review of the regeneration dynamics or North American boreal forest species. Can. J. For. Res. 29: 824-839.

Groot, A., and Carlson, D.W. 1996. Influence of shelter on night temperatures, frost damage, and bud break of white spruce seedlings. Can. J. For. Res. 26: 1531-1538.

Groot,A., Carlson, D.W., Fleming, R.L., and Wood, J.E. 1997. Small openings in trembling aspen forest: microclimate of white spruce and trembling aspen. NODA/NFP Technical Report TR-47.

Grossnickle, S.C. 2000. Ecolphysiology of northern spruce species. The performance of planted seedlings. NRC Research Press. Ottawa. 407 pp.

Haeussler, S., Coates, D., and Mather, J. 1990. Autecology of trembling aspen. In Autecology of Common Plants in British Columbia: A literature review. FRDA Report 158. 130-138.

Hibbs, D.E. 1982. Gap dynamics in a hemlock – hardwood forest. Can. J. For. Res. 12: 522-527.

Jarvis, P.G., James, G.B., and Landsberg, J.J. 1976. Vegetation and the atmosphere. Vol. 2. Edited by J.L. Monteith. Academic Press, London. pp 171-240.

Kimmins, J.P. 1997. Forest ecology a foundation for sustainable management. Prentice-Hall, Inc. New Jersey. 596 pp.

Langvall, O. and Örlander, G. 2001. Effects of pine shelterwoods on microclimate and frost damage to Norway spruce seedlings. Can. J. For. Res. 31: 155-164.

Langvall, O., and Löfvenius. 2002. Effect of shelterwood density on nocturnal near-ground temperature, frost injury risk and budburst date of Norway spruce. For. Ecol. Mgmt. 168: 149-161.

Leuning, R. and Cremer, K.W. 1988. Leaf temperatures during radiation frost. Part I. Observations. Agric. For. Meterol. 42: 121-133.

LI-COR, Inc. 1992. LAI-2000 Plant canopy analyzer operating manual. LI-COR Inc. Lincoln, Nebraska USA.

Lieffers, V.J., and Stadt, K.J. 1994. Growth of understory *Picea glauca, Calamagrostis canadensis* and *Epilobium augustifolium* in relation to overstory light transmission. Can. J. For. Res. 24: 1193-1198.

Lieffers, V.J., and Beck Jr., J.A. 1994. A semi-natural approach to mixedwood management in the prairie provinces. For. Chron. 70: 260-264.

Lieffers, V.J., Mugasha, A.G., and MacDonald, S.E. 1993. Ecophysiology of shade needles of *Picea glauca* saplings in relation to removal of competing hardwoods and degree of prior shading. Tree Physiol. 12: 271-280.

Lieffers, V.J., Messier, C., Stadt, K.J., Gendron, F., and Comeau, P.G. 1999. Predicting and managing light in the understory of boreal forests. Can. J. For. Res. 29: 796-811.

Lieffers, V.J., Pinno, B.D., and Stadt, K.J. 2002. Light dynamics and free-to-grow standards in aspen-dominated mixedwood forests. For. Chron. 78(1): 137-145.

Lundmark, T., and Hällgren, J. 1987. Effects of frost on shaded and exposed spruce and pine seedlings planted in the field. Can. J. For. Res. 17: 1197=1201.

Man, R., and Lieffers, V.J. 1997. Seasonal photosynthetic responses to light and temperature in white spruce (*Picea glauca*) seedlings planted under an aspen (*Populus tremuloides*) canopy and in the open. Tree Physiol. 17: 437-444.

Man, R., and Lieffers, V.J. 1999. Are mixtures of aspen and white spruce more productive than single species stands? For. Chron. 75: 505-513.

Martin, T.A., Hinckley, T.M., Meinzer, F.C., and Sprugel, D.G. 1999. Boundary layer conductance, leaf temperature and transpiration of *Abies amabilis* branches. Tree Physiol. 19: 435-443.

McCarthy, J. 2001. Gap dynamics of forest trees: a review with particular attention to boreal forests. Environ. Rev. 9: 1-59.

Messier, C., Doucet, R., Ruel, J. Claveau, Y., Kelly, C., and Lechowicz, M.J. 1999. Functional ecology of advance regen\eration in relation to light in boreal forests. Can. J. For. Res. 29: 812-823.

Nilsen, E.T., and Orcutt, D.M. 1996. Physiology of plants under stress: abiotic factors. John Wiley & Sons Inc. New York. pp. 401-444.

Oke, T.K. 1987. Boundary layer climates. 2nd ed. Methuen and Co. New York. pp. 339-356.

Örlander, G. 1993. Shading reduces both visible and invisible frost damage to Norway spruce seedlings in the field. Forestry 66(1): 27-36.

Ott, P. 1997. The use of indicator variables in non-linear regression. B.C. Ministry of Forests, Victoria, B.C. Biometrics Information Pamphlet No. 56.

Peterson, E.B., and Peterson, N.M. 1995. Aspen managers' handbook for British Columbia. Canada-British Columbia Partnership Agreement on Forest Resource Development. FRDA II. FRDA Report 230. Victoria, BC, Canada.

Ramsey, F.L., and Schafer, D.W. 1997. The statistical sleuth – a course in the methods of data analysis. Duxbury Press Belmont Ca. 742 pp.

Richardson, A.D., Berlyn, G.P., Ashton, P.M.S., Thadani, R., Cameron, I.R. 2000. Foliar plasticity of hybrid spruce in relation to crown position and stand age. Can. J. Bot. 78: 305-317.

Ross, M.S., Flanagan, L.B., and La Roi, G.H. 1986. Seasonal and successional changes in light quality and quantity in the understory of boreal forest ecosystems. Can. J. Bot. 64: 2792-2799.

Rowe, J.S. 1972. Forest regions of Canada. Canadian Forestry Service. Publication No. 1300.

Runkle, J.R. 1998. Changes in southern Appalachian canopy tree gaps sampled thrice. Ecol. 79(5): 1768-1780.

Schupp, E.W. 1995. Seed-seedling conflicts, habitat choice, and patterns of plant recruitment. Am. J.Bot. 82(3): 399-409.

Smith, D.M., Larson, B.C., Kelty, M.J., & Ashton, P.M.S. 1997. The practice of silviculture: applied forest ecology. John Wiley and Sons, Inc. New York. 537 pp.

Spittlehouse, D.L., and Stathers, R.J. 1990. Seedling Microclimate. Land Management Report #65 BC Ministry of Forests.

Sprugel, D.R., Brooks, J.R., and Hinckley, T.M. 1996. Effects of light on shoot geometry and needle *Abies amabilis*. Tree Physiol. 16: 91-98.

Stathers, R.J. 1989. Summer frost in young forest plantations. BC Ministry of Forests FRDA Report #73.

Stewart, J.D., Hogg, E.H, Hurdle, P.A.,Stadt, K.J.,Tollestrup, P., and Lieffers, V.J. 1998. Dispersal of white spruce seed in mature aspen stands. Can.J. Bot. 76: 181-188.

Valverde, T., and Silvertown, J. 1997. Canopy closure rate and forest structure. Ecology 78(5): 1555-1562.

Wang, J.R., Letchford, T., Comeau, P.G., Coppersmith, D. 2000. Foliar responses of understory *Abies lasiocarpa* of different degrees of release cutting in a *Betula papyrifera* and conifer mixed species stand. Scand. J. For. Res. 15: 611-620.

Wright, E.F., Coates, K.D., and Bartemucci, P. 1998. Regeneration from seed of six tree species in the interior cedar-hemlock forests of British Columbia as affected by substrate and canopy gap position. Can. J. For. Res. 28: 1352-1364.

3. The effect of light level on growth of white spruce under a trembling aspen canopy

3.1 Introduction

Mixtures of trembling aspen (*Populus tremuloides* Michx.) and white spruce (*Picea glauca* (Moench) Voss) are common on upland mesic sites of the mixedwood section of the western boreal forest (Rowe 1972; Beckingham and Archibald 1996). Shade intolerant aspen, with its more vigourous juvenile growth, generally dominates mixedwood sites during early development stages (Daniel et al. 1979; Lamontagne et al 1998; Beaudry et al. 1999) whereas moderately shade tolerant white spruce grows more slowly in the understory and begins to grow up through the aspen after age 60 (Thorpe 1992; Beaudry et al. 1999).

If the management goal in mixedwood stands is to promote the establishment, survival and vigour of white spruce while at the same time maintaining aspen on the site, an appropriate silvicultural system must be chosen. There are many techniques that can be employed prior to harvest that can provide spruce with a head start. Some of these include: advanced regeneration protection during logging (MacDonald 1996; Greene et al. 1999; David et al. 2001); spruce underplanting several years prior to overstory removal (Navratil 1996; Greene et al. 2002); seed source and seed bed management prior to harvesting (Greene et al. 1999; Greene et al. 2002); and various partial or strip cutting techniques to reduce windthrow problems (Bella and Brace 1988; Navratil 1996; Carlson and Groot 1997).

When white spruce is present in the understory of a young mixedwood stand following disturbance (as a result of natural or artificial regeneration), its growth can be severely limited by competition from aspen. The growth potential of spruce is influenced by competition for light, water and nutrients (Brand 1991) but it is difficult to separate these factors (Cannell and Grace 1993) and light is commonly used as a surrogate measurement of the overall competition level experienced by the spruce. Much of the growth suppression of the white spruce comes from inadequate light levels. Maximum photosynthesis of white spruce shoots occurs between 40% and 60% of full sunlight (Logan 1969; Coates and Burton 1999; Spittlehouse and Stathers 1990) but there is evidence that maximum diameter and stem volume growth occurs at 100% full sunlight probably because radial growth allocation typically occurs after other growth needs have been met (Logan 1969; Comeau et al. 1993; Oliver and Larson 1996; Coates and Burton 1999).

Mixedwood stands naturally go through a self-thinning process. During the first 10 – 15 years, the stands' leaf area increases until it reaches a competition bottleneck (Lieffers et al. 2002) where light levels are very low. The stand then begins to break up and gaps are formed and light levels gradually begin to increase. Thinning or creating gaps within the stand can speed up the onset of these increased light levels.

The response of trees to differences in light levels is dependent on their shade tolerance. Species that have greater shade tolerance are generally able to take better advantage of increased light from gaps or even from small changes in ambient diffuse light levels via quick modification of physiological processes and morphological characteristics (Chen 1997; McCarthy 2001) – this ability is often referred to as plasticity. As trees age, their plasticity to respond to a changing light environment declines (Richardson et al. 2000). Douglas-fir and Englemann spruce (both considered moderately shade tolerant) are plastic in the absolute above ground to below ground biomass growth ratio, height/diameter ratio and specific leaf area (SLA) whereas these ratios do not change much in shade intolerant ponderosa pine (Chen 1997). Shade intolerant lodgepole pine displays less morphological plasticity with emphasis given to height growth and high apical dominance under all light regimes. Chen (1997) found true firs more plastic in shoot and crown morphology than either spruce or pine in relation to light availability.

Specific leaf area – measured as projected leaf area (cm^2)/leaf mass in grams, is higher in leaves developed in low light because individual needles are usually thinner and broader than sun needles (Awada and Redmann 2000; Chen 1997; Messier et al. 1999; Aphalo and Ballaré 1995; Duchesneau 2000). This is beneficial under low light conditions as it allows plants to display greater surface area for the capture of light and maintain a positive photosynthetic/respiration balance (Sprugel et al. 1996).

Shade intolerant species tend to allocate photosynthate to height growth, whereas shade tolerant species allocate more photosynthates to lateral growth to capture more light resources in light limiting environments (Oliver and Larson 1996, Chen 1997, Messier et al. 1999). Higher root/shoot ratios for intolerant species indicate that there is more available photosynthate for distribution throughout the tree (Grossnickle 2000). Higher total photosynthate production in shade intolerant species means that there is more carbon left over, after maintenance and foliar and fine root construction costs have been met, to allow allocation of carbon to large root and stem production.

There may be a maximum height in a given environment at which a tree can 'wait' which is determined by the net photosynthate remaining after root, foliage, maintenance and construction costs are met. Since maintenance requirements will increase with increasing tree size, light requirements to meet these maintenance costs are also thought to increase (Givnish 1988). As a result, allocating growth to height might be detrimental to survival when increased height is not rewarded by increased light availability (Messier et al. 1999; Claveau et al. 2002). A maximum sustainable height or waiting height can be proposed for species of different shade tolerances with the most tolerant having the smallest waiting size within the smallest canopy gaps (Messier et al. 1999).

The Michaelis-Menten function has been used by some authors to describe the relationship between growth (height, diameter or volume) and relative irradiance over the growing season (Pacala et al. 1994; Coates and Burton 1999; Wright et al.1998). This relationship describes the ability of shade tolerant species to have a greater increase in growth per unit increase in light at low light levels but have lower growth rates per unit increase in light at high light levels (Coates and Burton 1999).

Shade tolerant species are able to survive and grow (although slowly) at low light levels. Kobe and Coates (1997) found that shade tolerant species have a more rapid decline in probability of mortality at low previous growth rates with only slight increases in the rate whereas shade intolerant species had a much slower decline. The ability of young trees to survive in low light conditions determines what trees will be there to respond to future increases in light and should be considered a component of stand growth and dynamics (Chen 1997; Wright et al. 1998).

In general, morphological adaptations are permanent once a sun or shade leaf is constructed (Sprugel et al. 1996; Wang et al. 2000; Lieffers et al. 1993). If a stand is opened up in late spring after the new leaves have developed, there is often a period of stress from the sudden high light levels. White spruce in mixedwood stands is able to quickly acclimate to increased irradiance following removal of overtopping hardwoods (Man and Lieffers 1997). This may be partially because needle development in the spring prior to hardwood leaf-out occurred in higher light conditions which may have allowed development of characteristics more similar to sun leaves (Man and Lieffers 1997). Changes in chlorophyll a/b ratios and increases in protective carotenoid pigments may be some of the acclimation responses that occur relatively quickly following hardwood removal (Lieffers et al. 1993).

Even 177 year old white spruce advanced regeneration responds to release from competition (Crossley 1976) but smaller trees generally respond more quickly than larger trees (Ruel et al. 2000; Kneeshaw et al.2002). Conversely very small seedlings often show poor survival when overstory is removed. This poor survival may be because of poor root system development (Logan 1969) making seedlings vulnerable to water stress in their now exposed position (Ruel et al. 2000). Advanced regeneration of shade tolerant species that had high pre-release height growth rates and vigour respond better to release than those with low previous growth rates and vigour (Ruel et al. 2000). The height growth response by a tree to release is typically slower than diameter growth responses (Ruel et al. 2000; Kneeshaw et al. 2002).

Wright et al. (2000) suggest that understory trees may go through alternating periods of suppression and release before they reach upper canopy positions. Their study suggests that more shade tolerant species show less decline in growth over time during suppression in comparison to shade intolerant species which show greater reductions in radial growth rates during suppression periods.

Trees generally experience a delay in their response to release. Kneeshaw et al. (2002) found that height growth of both lodgepole pine and Douglas-fir decreased following removal of the overstory canopy, and was not followed by a growth increase until two years later. A one year reduction in stem radial growth was also noted.

The first few competitors had the greatest influence on growth reductions for white spruce growing under a hardwood canopy in the Bas- Saint-Laurent region of Quebec with additional competitors having a significant but marginal impact on growth losses (Jobidon 2000). Treatments that remove all competitors should therefore give the best growth response. Consideration of other factors such as the importance of timely treatments and high costs for treatments that are often required more than once and the potential for frost and insect problems means that high levels of removal are not necessarily the best overall choice.

Several authors have examined the effect of light absorbance or light capture on growth (Pacala et al. 1996; Brunner and Nigh 2000; MacFarlane et al. 2002). It follows that a tree that is able to absorb or capture more of the available light would have improved growth rates. Pacala et al. (1996) found a trade-off between trees that grow quickly under high light levels (generally more shade intolerant species) and those that grow slowly under high light conditions (generally more shade tolerant species). Trees that grow quickly under high light tend to cast relatively little shade (have low leaf area density), have low survivorship under low light and have low dispersal whereas slow growers tend to cast more shade, have higher survivorship under low light and low dispersal. It is suggested that shade tolerant species, although they may have more needles to capture available light which can lead to self-shading, have higher photosynthetic rates than shade intolerant species under low light conditions which offsets the loss to the overall carbon gain of a tree. Pacala et al. (1993) found that with increasing shade tolerance, the rate of height growth at high light levels decreased and the rate of height growth at low light levels and the rate of radial growth at any light levels does not change.

Brunner and Nigh (2000) found a good relationship between diameter (DBH) increment or bole volume increment and leaf area (weighted by the crown volume represented by the sample point) when measured over a 18 year period and a still significant but poorer R^2 value for diameter increment measured over a shorter 4 year period. They also found that for suppressed trees leaf area was a poor predictor of bole volume growth. MacFarlane et al. (2002) used methods similar to those employed by Brunner and Nigh (2000) to examine growth rates over an 8 year period for loblolly pine trees aged 8 through 16. They found significant relationships between height, basal area or stem volume increment and weighted leaf area. The greatest amount of total variability was explained by weighted leaf area in the model predicting stem volume increment and the least for height increment.

The objectives of this study are to determine the effect of different light levels on the growth of white spruce growing in the understory of young aspen stands and to examine relationships between light capture and growth of small white spruce. These relationships provide a basis for evaluating the effects of overtopping aspen on growth.

3.2 Materials and Methods

In order to relate the level of light and temperature created in the circular openings to growth of white spruce under different light levels, individual trees occurring in natural openings across a broad range of light levels were selected.

Forty-five white spruce trees were chosen near Slave Lake Alberta, from the same general area as was used to create circular openings of increasing size in component one of this project (Chapter 2). Nine stands were selected for this study. Table 3.1 describes the location and major features of these stands. Five spruce trees were selected in each of these nine stands to sample the range of light levels experienced in the first component of the study.

Table 3.1. Stand locations and average age, height, basal area and density of aspen in stands where white spruce were sampled near Slave Lake

Block	Latitude (N)	Longitude (W)	Age (yrs)	Aspen height (m)	Ba/ha m^2/ha	Density (sph)
66N	55° 30′ 52″	113° 47′ 17″	6	3	6.9	28,700
66S	55° 30′ 48″	113° 47′ 26″	6	2.5	3.6	14,880
69	55° 30′ 24″	113° 45′ 34″	6	3	12.3	37,700
14A	55° 25′ 58″	114° 34′ 07″	9	4.25	7.2	25,000
14B	55° 26′ 05″	114° 34′ 06″	9	3.75	8.3	20,100
Fawcett	55° 19′ 08″	114° 04′ 23″	10	4.5	13.9	21,680
35A	55° 30′ 25″	114° 16′ 48″	16	7.5	21.2	22,200
35B	55° 30′ 24″	114° 17′ 03″	16	7.5	22.2	18,600
Husky	55° 28′ 05″	114° 10′ 33″	13	7.5	14.5	17,200

BA/ha = basal area in m^2 per hectare; sph = stems per hectare

Trees were located and marked in late spring prior to aspen leaf-out to make location easier. In mid-July, a 3.99 m radius circular plot was established with each of the spruce at its center and species and dbh were tabulated for each tree 1.3 m and taller within the plot. Four aspen trees within each plot were measured for crown width and an average determined. These plot measurements provide data to characterize density and basal area of deciduous competitors around each spruce.

LAI-2000 plant canopy analyzers with LAI-2050 optical light sensors and 90° view restrictors were used to obtain measurements of light transmittance immediately adjacent to the bottom, middle and top of each tree crown. Other studies (Comeau et al. 1998; Gendron et al.1998) indicate that diffuse non-interceptance (DIFN) measurements provided by the LAI-2000 sensors provide good estimates of growing season transmittance. The average of these measurements was used to represent the light conditions experienced by the tree. Crown radius was measured in each of 4 cardinal directions and used to calculate: average crown radius of the white spruce in 2002 and for each proceeding year back to 1999. Tree height was also measured in 2002 and measurements of height for each proceeding year were also recorded back to 1999. These component measurements of the crown structure were then used to estimate spruce crown surface area (CSA) in 1999 based on the assumption of a conical shaped crown (CSA = average crown radius * length of crown side *π, where the length of the crown side = sqrt(radius^2+crown height^2)) (Hatch et al. 1975).

The 45 trees were then cut down. A stem disc was cut from the base of the each stem and taken to the laboratory for measurement of root collar diameter in 1999 and 2002. Root collar diameter and stem height in 1999 and 2002 were used to estimate stem volumes at these two points using the equation: stem volume = π (root collar diameter/2)^2*height * 0.6. This equation assumes that the stem is comprised of a cylinder that makes up 2/5 of the total height and a cone that makes up 3/5 of the total height.

Following cutting, 20 of these 45 trees were taken in their entirety to a large opening and set to stand freely and LAI-2000 measurements were taken - at the bottom of the crown with the light sensor, fitted with a 90° view restrictor, placed adjacent to the tree stem and looking out in each of 4 cardinal directions. Matching open sky readings were taken with the sensor pointing in the same cardinal directions. DIFN values were calculated by comparing stem and open sky measurements, and absorbance was calculated as 1-DIFN.

To estimate the amount of light which could be absorbed by each of these 20 trees in their original growing conditions, average transmittance at the tree crown surface back in its original position under the aspen canopy was multiplied by the absorbance of the crown in the open.

These 20 trees were taken back to the lab and a sample of needles was taken from the top, middle and bottom crown positions and scanned using an EPSON Expression 1680 optical scanner with WIN SEEDLE™ 2001a software for seeds and conifer needle analysis to determine if there was a difference between specific leaf area (SLA – projected leaf area measured on a fresh weight basis/dry weight) of the needles from these different crown positions. All needles from all 20 trees were removed from the branches and oven dried at 65°C for 48 hours. The needles were weighed and each weight was multiplied by the average SLA in mm^2 /g determined from foliage samples taken from the top, middle and base of the crown and then converted to a projected leaf area basis. Leaf area of each tree was calculated by multiplying SLA by total needle dry weight measured for the tree.

Analysis of relationships between spruce growth and light levels underneath aspen canopies for the Fort St. John, B.C. area is based on measurements collected in research plots near Siphon Creek (approximately 85 km northeast of Fort St. John - 56°30′ N and 120°30′ W). These research plots were brush-bladed in the early winter of 1986/87, windrow piles were burned in spring 1988 and planted with 1600 sph of white spruce in late spring 1988 and the trial was established in 1990 (Coopersmith and Hall 1999).

Aspen was thinned to either 10,000, 5,000 or 0 sph in 1990 and additional spruce was planted as needed to increase spruce stocking levels to those outlined in Table 3.2.

Table 3.2. Siphon Creek research trial original densities

Plot	Aspen density (sph)	White spruce density (sph)
2	10,000	500
5	10,000	700
6	0	1,300
14	5,000	900
22	5,000	1,500

Measurements of crown radius in 4 cardinal directions were taken to determine: average crown radius of the white spruce in 2001 back to 1999 and crown height in 2001 back to 1999. These component measurements were used to determine CSA in 1999 as described above for the white spruce sampled near Slave Lake. Root collar diameter and total height were measured in 1998 and in 2001 and used to estimate average annual stem volume growth over the period. Diffuse light transmittance was determined in 2001 using LAI-2000 plant canopy analyzers, with 90° view restrictors, taking measurements at a mid-crown position or at 2.5 meters in cases where mid-crown could not be reached.

3.2.1 Data Analysis

Data analysis was completed using SAS version 8.1 (SAS Institute Inc. 1999-2000). Multiple linear regression analysis was used to examine the relationship between periodic stem volume growth and average transmittance values experienced by the tree and the crown surface area at the beginning of the measurement period. Logarithmic transformation of the dependent variable was used to achieve homogeneity of variances.

Residual plots (Figure 3.1 and 3.2) indicate that the residuals of values predicted by the log-transformed data show a good scatter of points around zero.

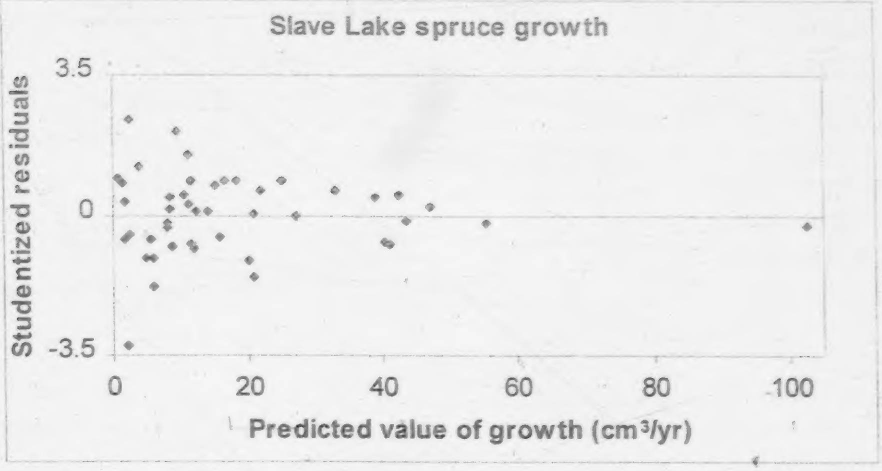


Figure 3.1. Scatterplot of studentized residual values and predicted values of periodic stem volume growth as produced from the relationship given by the model Lngrowth = Ln(CSA00) + Ln (DIFN02) for white spruce near Slave Lake.

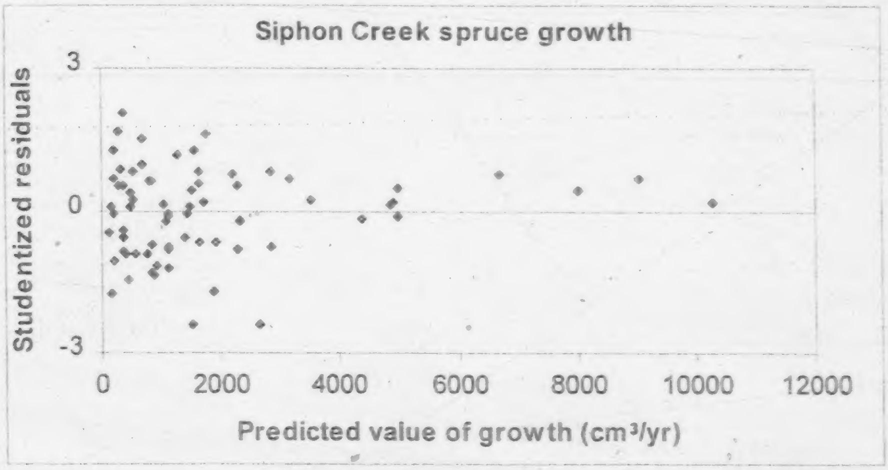


Figure 3.2. Scatterplot of studentized residual values and predicted values of periodic stem volume growth as produced from the relationship given by the model Lngrowth = Ln(CSA99) + Ln (DIFN01) for white spruce near Siphon Creek.

PROC GLM was used to test whether SLA measurements from top, mid and bottom crown positions were statistically different from each other. This test was negative with all three positions producing values that were not significantly different ($\alpha = 0.05$).

Linear regression was also used to examine the relationship between leaf area and crown surface area, the relationship between light absorption by trees in the open and their leaf area, and to examine relationships between tree growth and light absorption by the tree under the canopy. Residual plots of several of these relationships (Figure 3.3) indicate that the residuals of values predicted by the log-transformed data show a good scatter of points around zero.

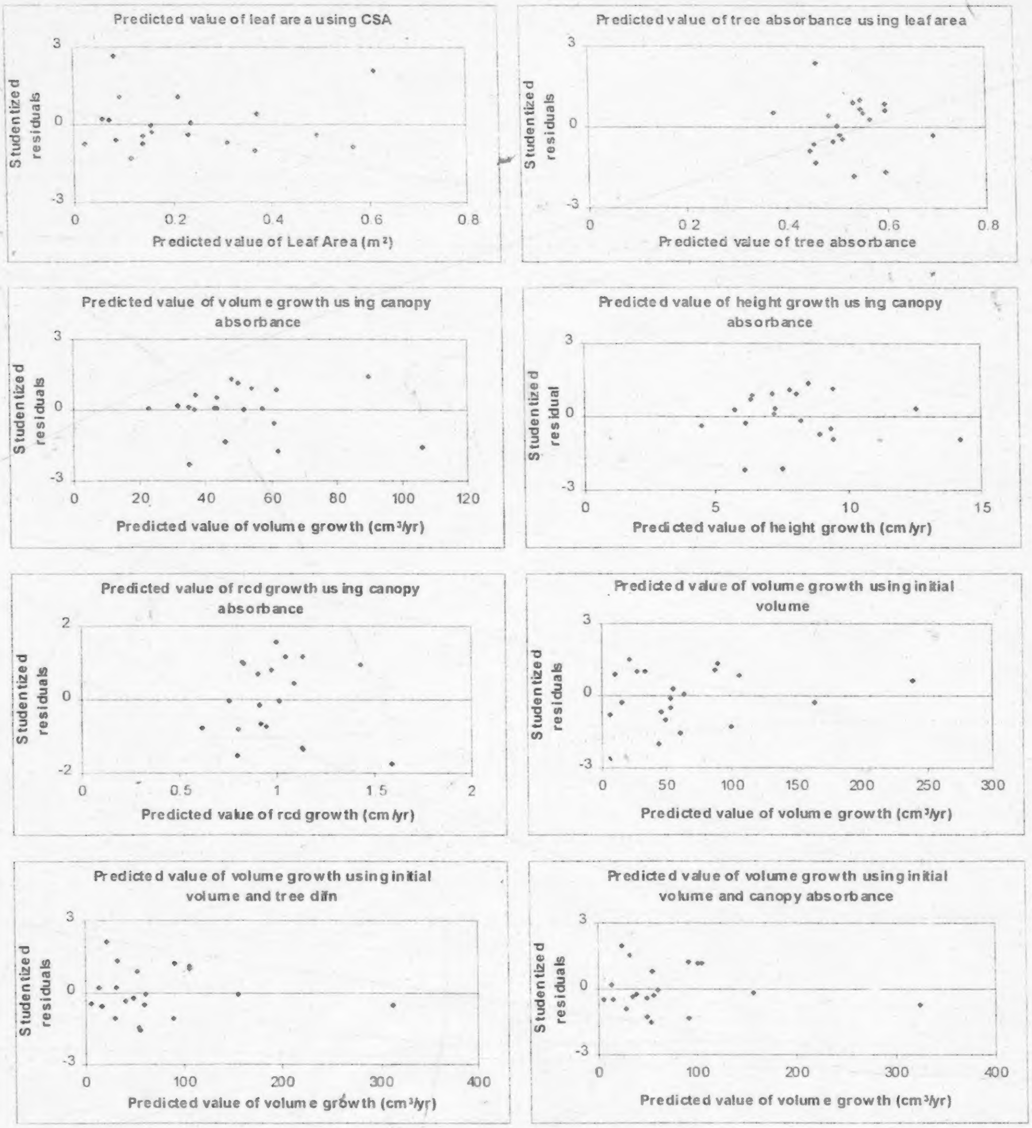


Figure 3.3. Studentized residual plots of various models using logarithmically transformed variables as produced by the relationships given by the models in figures 3.5 to 3.9.

3.3 *Results*

3.3.1 Growth versus DIFN and initial crown surface area

White spruce in stands located near Slave Lake, Alberta were generally smaller than those located in stands near Siphon Creek (85 km northeast of Fort St. John, B.C.). The Slave Lake spruce ranged in height from 38 to 240 cm, root collar diameter ranged from 4.5 mm to 22 mm, crown radius ranged from 13.4 to 54 cm and transmittance from 0.04 to 0.84 (Table 3.3).

Table 3.3. Ranges of characteristics of white spruce sampled near Slave Lake

Block	Height '02 (cm)	RCD '02 (mm)	Avg.CR '02 (cm)	DIFN '02
Fawcett	40-96	5-10	13.4-22.4	0.13-0.29
14A	103-151	9.5-16	23.6-41.3	0.21-0.59
14B	110-183	9.5-16	23.3-42.4	0.18-0.66
35B	82-181	10-17.5	22.4-41.8	0.08-0.51
35A	38-169	4.5-12	17.4-45.4	0.06-0.34
Husky	68-187	6.5-16	21-47.1	0.04-0.41
66S	48-166	4.5-19	12.8-40.1	0.36-0.84
66N	89-240	10-22	23.8-54	0.14-0.71
69	64-112	10-12	19.6-35.8	0.08-0.31

RCD = root collar diameter; Avg CR = average crown radius; DIFN = diffuse non-interceptance.

Table 3.4. Ranges of characteristics of white spruce sampled at Siphon Creek

Plot	Height '01 (cm)	RCD '01(mm)	Avg CR '01 (cm)	DIFN '01
2	139-484	27-65	45.6-111.9	0.27-0.56
5	158-476	15-66	54.5-108.5	0.11-0.26
6	301-642	63-146	76.8-166.1	0.52-0.81
14	250-471	34-76	68.4-109.5	0.10-0.20
22	231-576	34-70	58-135	0.15-0.37

The white spruce near Siphon Creek ranged in height from 139 to 642 cm, root collar diameter ranged from 15 mm to 146 mm, crown radius ranged from 45.6 to 166.1 cm and transmittance from 0.10 to 0.81 (Table 3.4).

The crown radius of overstory trembling aspen ranged from 35 cm to 148 cm in the area surrounding measured white spruce near Slave Lake while average crown radius of aspen near Siphon Creek ranged from 45 to 214 cm (Table 3.5). Density of aspen within a 3.99 meter radius of the white spruce near Slave Lake ranged from 3,000 to 27,200 stems per hectare and basal area ranged from 0.8 -23.6 m^2/ha (Table 3.5).

Table 3.5. Ranges of characteristics of overstory trembling aspen

Location	Average aspen height (m)	Block	Crown radius aspen (cm)	Density (sph)	Ba/ha m^2/ha
Slave Lake	4-5	Fawcett	68-100	12,400-22,600	5.5-11.6
Slave Lake	4-4.5	14A	58-90	13,400-21,200	3.3-7.2
Slave Lake	3.5-4	14B	35-98	8,600-18,400	1.8-10.6
Slave Lake	7-8	35B	90-148	5,600-20,400	8.8-23.6
Slave Lake	7-8	35A	75-108	9,800-20,000	6.3-19.7
Slave Lake	7-8	Husky	50-105	6,600-18,600	5.1-16.6
Slave Lake	2-3	66S	48-73	3,000-13,800	0.8-4.1
Slave Lake	2.5-3.5	66N	50-73	8,600-22,600	2.8-7.3
Slave Lake	2.5-3.5	69	60-83	12,600-27,200	6.2-10.3
Siphon Creek	4.5-8	2	59-181	–	–
Siphon Creek	5.6-11.9	5	45-156	–	–
Siphon Creek	N/A	6	N/A	–	–
Siphon Creek	4.1-8.9	14	80-166	–	–
Siphon Creek	7.8-10.4	22	124-214	–	–

BA/ha = basal area in m^2 per hectare; sph = stems per hectare

There is a significant relationship between linearalized (log transformed) height growth (measured as periodic growth from 1999 to 2001) and crown surface area at the beginning of the measurement period and light transmittance at the crown surface for white spruce near Siphon Creek (Table 3.6). The spruce near Slave Lake also shows a significant relationship for this growth measurement but the intercept term was not significant in this model (Table 3.6).

Root collar diameter growth is explained by a model that combines initial crown surface area and light transmittance with moderate R^2 values (Table 3.6) although the intercept term is not significant for the Siphon Creek spruce trees.

The highest R^2 values are found for the relationship between stem volume growth and initial crown surface area and light transmittance at the crown surface (Table 3.6). All coefficients and the intercept term are highly significant with Prob > |T| of < 0.0001.

Table 3.6. R^2 (RMSE) values for regression models using log transformed variables

	Initial CSA	DIFN	Combined CSA/DIFN
Siphon Creek			
Height growth (m/yr)	0.482 (0.37)	0.242 (0.44)	0.562 (0.34)
RCD growth (cm/yr)	0.323 (0.41)	0.420 (0.38)	0.564 (0.33)*
Stem volume growth (cm^3/yr)	0.733 (0.59)	0.384 (0.90)	0.866 (0.42)
Slave Lake			
Height growth (m/yr)	0.426 (0.38)*	0.202 (0.45)	0.677 (0.29)*
RCD growth (cm/yr)	0.293 (0.41)	0.160 (0.45)	0.489 (0.35)
Stem volume growth (cm^3/yr)	0.737 (0.64)	0.045 (1.21)**	0.814 (0.54)

* intercept term not significant at α=0.05; ** coefficient not significant at α=0.05; all other terms and coefficients are significant at α=0.05.

In order to test whether the white spruce measured near Siphon Creek and those measured near Slave Lake could be combined into one general model, extra sums of squares testing (Ott 1997, Ramsey and Schafer 1997) was carried out. The test showed that the coefficients for the two locations are significantly different (p=0.0021) and a single model should not be used.

Because of the 3 separate height classes of stands near Slave Lake, extra sums of squares testing was done to test whether these three height classes could be described by a common model. This test revealed that the coefficients were not significantly different from each other and that one model could be used for the three Slave Lake height groups ($p=0.084$).

Figure 3.4 illustrates relationships between stem volume growth and the two independent variables – DIFN and CSA. At low light transmittance levels (0.1), periodic stem volume growth for young saplings with crown surface area of 15,000 cm^2 near Slave Lake, is predicted to be 43 cm^3/yr while for a smaller tree with CSA of 7,000 cm^2 predicted growth is 14 cm^3/yr. For moderate light transmittance levels (0.35), CSAs of 15,000 cm^2 would yield growth of 77 cm^3/yr and a CSA of 7,000 cm^2 would yield 25 cm^3/yr. With high light transmittance levels (0.80), a CSA of 15,000 cm^2 would yield a growth rate of 112 cm^3/yr and a CSA of 7,000 cm^2 would yield 36 cm^3/yr.

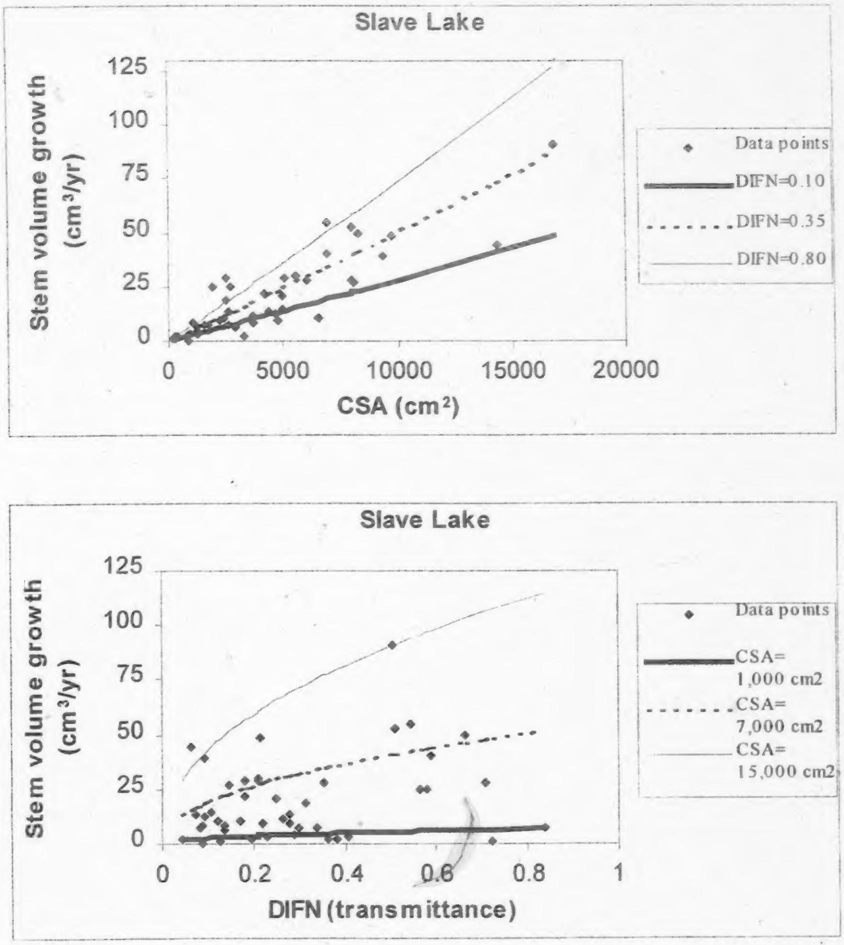


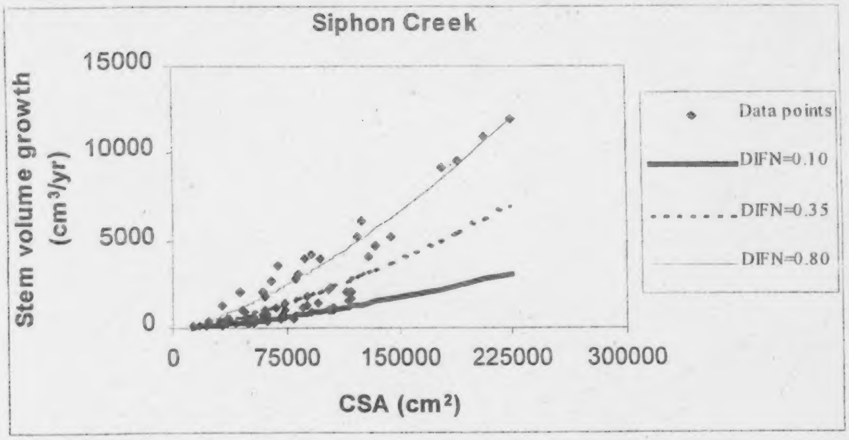
Figure 3.4. Scatterplot showing relationship between periodic growth and crown surface area in 2000 and transmittance (DIFN) in 2002. The lines are described by the equation: Ln(stemvol growth) =-5.191304 +1.041593* Ln (CSA00) + 0.463972* Ln (DIFN02); $R^2 = 0.8144$, RMSE = 0.539, n=45.

Young saplings near Slave Lake with very low crown surface areas (1,000 cm^2) displayed very little difference (4 cm^3/yr) between growth rates at high (0.8) and low (0.1) light levels, whereas the difference in growth rates between light levels of 0.1 and 0.8 was 31 cm^3/yr for CSA levels of 7,000 cm^2 and 70 cm^3/yr for CSA levels of 15,000 cm^2 (Figure 3.4).

For the larger white spruce near Siphon Creek growing in low light transmittance levels (DIFN=0.1), periodic stem volume growth is predicted to be 166 cm^3/yr for saplings with crown surface area of 30,000 cm^2 and 956 cm^3/yr for larger trees with CSA of 100,000 cm^2 (Figure 3.5). For moderate light transmittance levels (DIFN=0.35), CSAs of 30,000 cm^2 would yield growth of 373 cm^3/yr and a CSA of 100,000 cm^2 would yield 2,154 cm^3/yr. With high light transmittance levels (DIFN=0.80), a CSA of 30,000 cm^2 would yield a growth rate of 637 cm^3/yr, a CSA of 100,000 cm^2 would yield 3,680 cm^3/yr and a CSA of 200,000 cm^2 would yield 10,099 cm^3/yr.

White spruce saplings near Siphon Creek with low (relative to their size) crown surface areas (15,000 cm^2) displayed slight differences (172 cm^3/yr) between growth rates at high (0.8) and low (0.1) light levels, whereas the difference in growth rates between light levels of 0.1 and 0.8 was 472 cm^3/yr for CSA levels of 30,000 cm^2, 2,723 cm^3/yr for CSA levels of 100,000 cm^2 and 7,474 cm^3/yr for CSA levels of 200,000 cm^2 (Figure 3.5).

Comparison of stem volume growth rates between Siphon Creek and Slave Lake white spruce indicate that for a given light level the rate is always significantly more for the larger Siphon Creek spruce. The difference increases as the light level increases (Table 3.7).



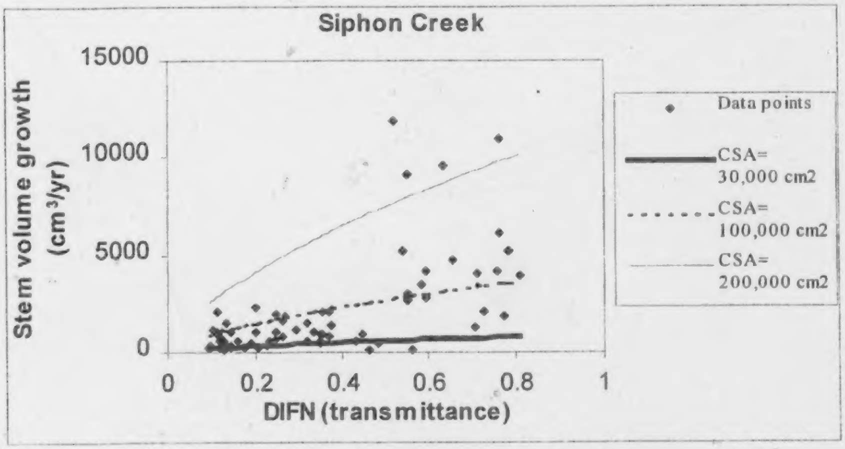


Figure 3.5. Scatterplot showing relationship between periodic growth and crown surface area in 1999 and transmittance (DIFN) in 2001. The lines are described by the equation: Ln(stemvol growth) =-8.424382 +1.457476* Ln (CSA99) + 0.648499* Ln (DIFN01); R^2= 0.8658, RMSE = 0.424, n=71.

Table 3.7. Comparison of stem volume growth rates for white spruce with a CSA of 15,000 cm^2 at low moderate and high light levels near Siphon Creek and Slave Lake

Location	DIFN	Initial CSA (cm^2)	Stem vol.growth rate (cm^3/yr)
Siphon Creek	0.10	15,000	60
Slave Lake	0.10	15,000	43
Siphon Creek	0.35	15,000	136
Slave Lake	0.35	15,000	77
Siphon Creek	0.80	15,000	232
Slave Lake	0.80	15,000	112

3.3.2 Growth versus light absorbance

For the 20 white spruce that were set up in the open to determine tree absorbance and had leaf area measured in the lab, a good relationship (R^2=0.857) was found between leaf area and the more easily estimated crown surface area. Figure 3.6 illustrates that for small spruce growing under aspen near Slave Lake, a crown surface area of 15,000 cm^2 would equal a leaf area of approximately 0.4 m^2 and a surface area of 5,000 cm^2 approximately 0.1 m^2.

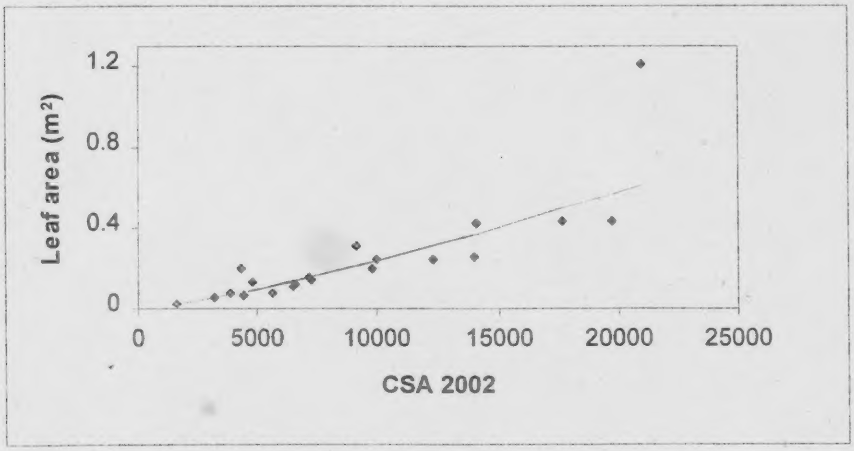
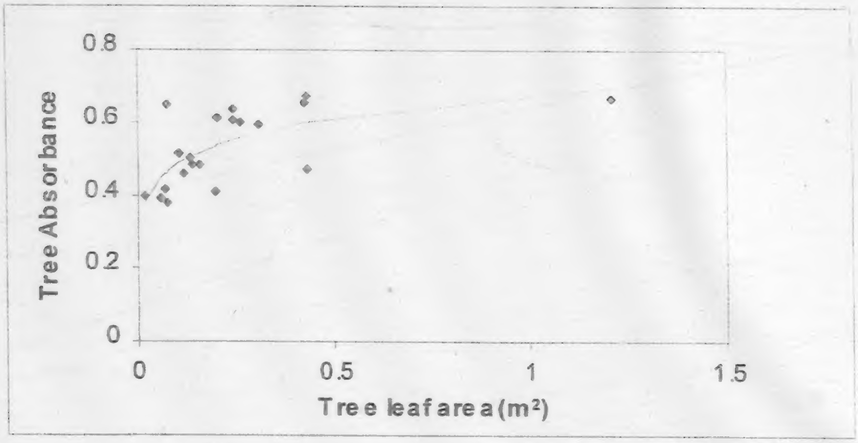


Figure 3.6. Scatterplot showing the relationship between tree leaf area (LA) and crown surface area (CSA). The line is described by the equation: Ln(LA)= -13.141 + 1.272 * Ln(CSA); R^2=0.857; RMSE=0.356; n=20.

There is also a significant, though moderate, relationship between the absorbance of a tree in the open and leaf area of the tree (Figure 3.7a). The moderate R^2 value may result from possible error in absorbance measurements taken using the LAI-2000 plant canopy analyzer in that it is difficult, when placing the light sensor (oriented in a given cardinal direction), to ensure that the sensor is not looking directly at a branch. The small sample size in this case (20 trees) would give such an occurrence greater influence. Crown surface area shows a very similar trend in its relationship with tree absorbance (Figure 3.7b) with a moderate R^2 value.

a



b

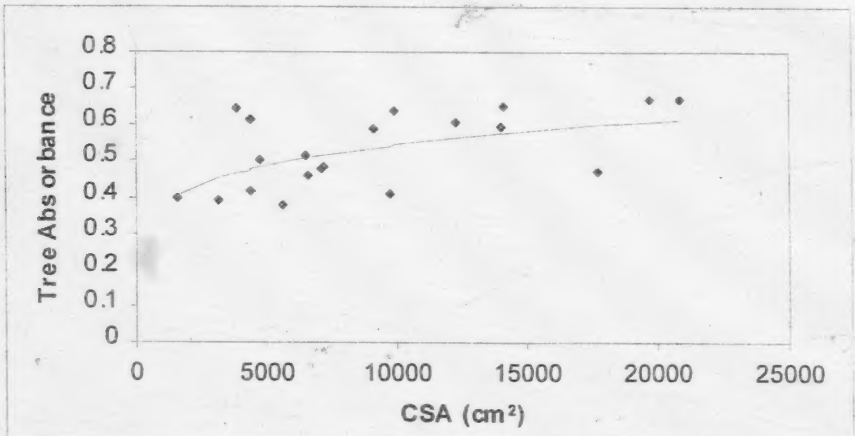


Figure 3.7 (a-b). Scatterplots showing the relationship between tree absorbance in the open and tree leaf area (a) or crown surface area (b). The lines describe the equations: a) Ln(Tree Absorbance)= -0.392442 + 0.146351 * Ln(LA); R^2= 0.4619; RMSE=0.1489; n=20 and b) Ln(Tree Absorbance)= -2.1374 + 0.166125 * Ln(CSA); R^2= 0.3156; RMSE=0.168; n=20 .

Canopy absorbance (absorbance of a spruce tree back in its canopy position – calculated as tree absorbance multiplied by the transmittance through the canopy), does have an effect on the growth of the tree. Canopy absorbance is a significant variable in explaining both height and diameter growth but canopy absorbance on its own has a poor relationship with stem volume growth (Figure 3.8 a-c).

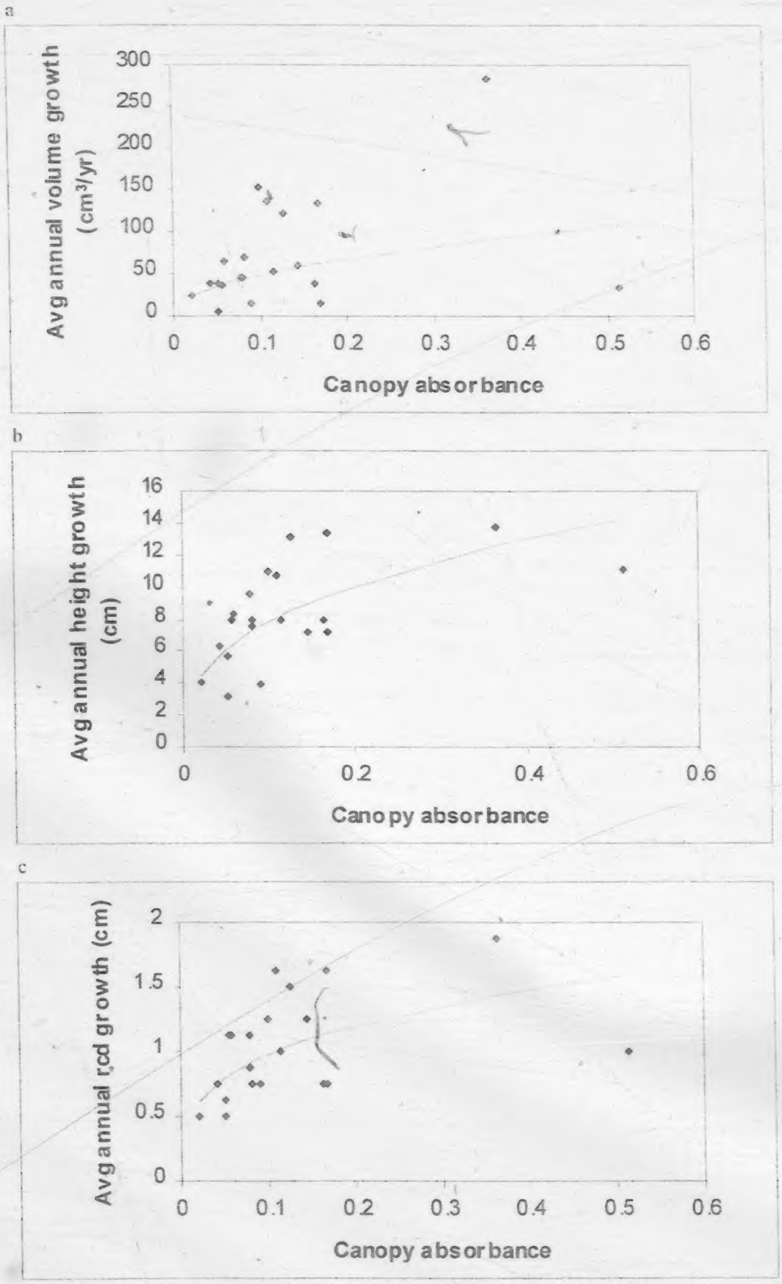


Figure 3.8 (a-c). Scatterplots showing the relationship between stem volume, height and root collar diameter average annual growth and canopy absorbance. The lines are represented by the equations: a) Ln(Vol)= 4.985818 + 0.4817 *Ln(CanAbs); R^2=0.1371; RMSE= 0.906, n=20; b) LnHt= 2.899725 + 0.365489 * Ln(CanAbs); R^2=0.4152; RMSE =0.324; n=20; and c) Ln(Rcdgrowth)=0.6629 + 0.299 * Ln(CanAbs); R^2= 0.3275; RMSE=0.322; n=20. For equation (a), canopy absorbance is not a significant variable (Prob |T| = 0.1080).

There is a significant relationship between stem volume growth and initial stem volume (Figure 3.9). Root collar diameter growth is also explained by initial diameter but the relationship only has an R^2 value of 0.36, whereas height growth has a highly insignificant intercept term when related to initial height.

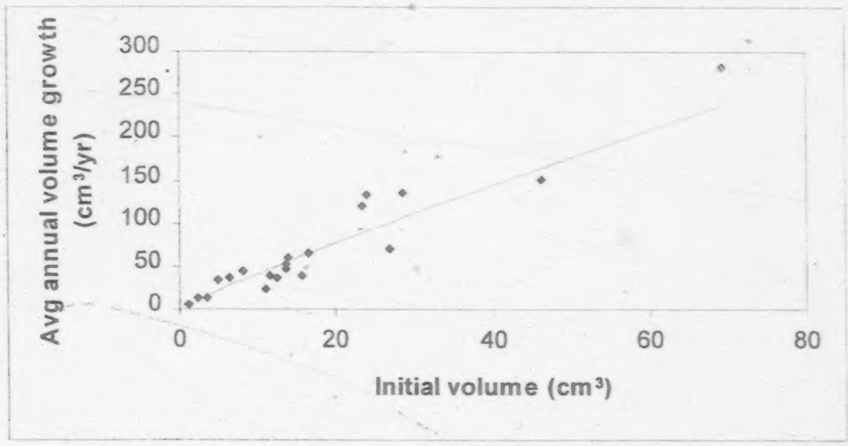


Figure 3.9. Scatterplot showing the relationship between stem volume growth and initial volume. The line is represented by the equation: Ln(Vol growth)=1.606897 + 0.912813*Ln(Initial volume); R^2=0.9026; RMSE=0.3045; n=20.

A model that combines canopy absorbance and initial tree size measurements yields insignificant intercept terms for both height and root collar diameter growth but stem volume growth has a significant relationship with initial stem volume and canopy absorbance (Figure 3.10). For a canopy absorbance of 0.05 for a tree with an initial stem volume of 50 cm^3 you could expect average annual volume growth of 139 cm^3/yr while a canopy absorbance of 0.4 for this same sized tree would yield a volume growth of 251 cm^3/yr.

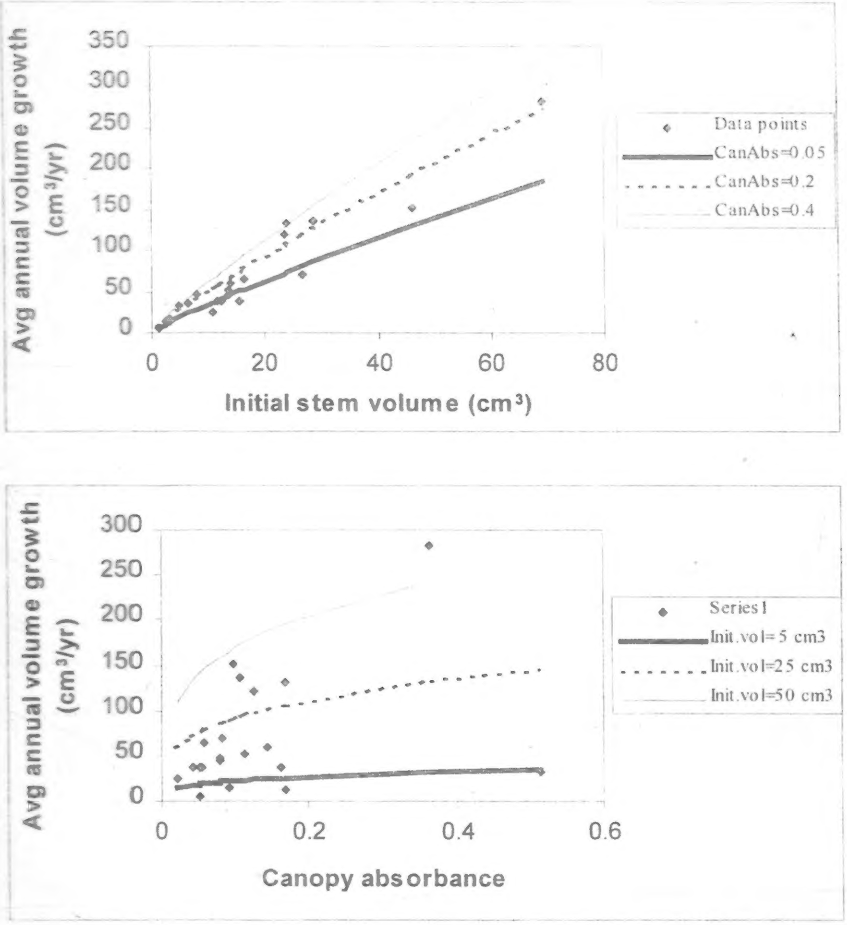


Figure 3.10. Scatterplot showing the relationship between average annual stem volume growth and the absorbance of a tree in the canopy and tree volume at the beginning of the measurement period. The lines are described by the equation: Ln(Vol growth)= 2.347 + 0.282*Ln(CanAbs) + 0.878*Ln(Init.vol); R^2=0.948; RMSE=0.229; n=20.

There is also a very good relationship between stem volume growth and initial stem volume and light transmittance to the canopy surface (Figure 3.11). This relationship predicts that volume growth of a 50 cm^3 tree would be 150 cm^3/yr in low light conditions (DIFN=0.1) and 227 cm^3/yr in a large opening (DIFN=0.5).

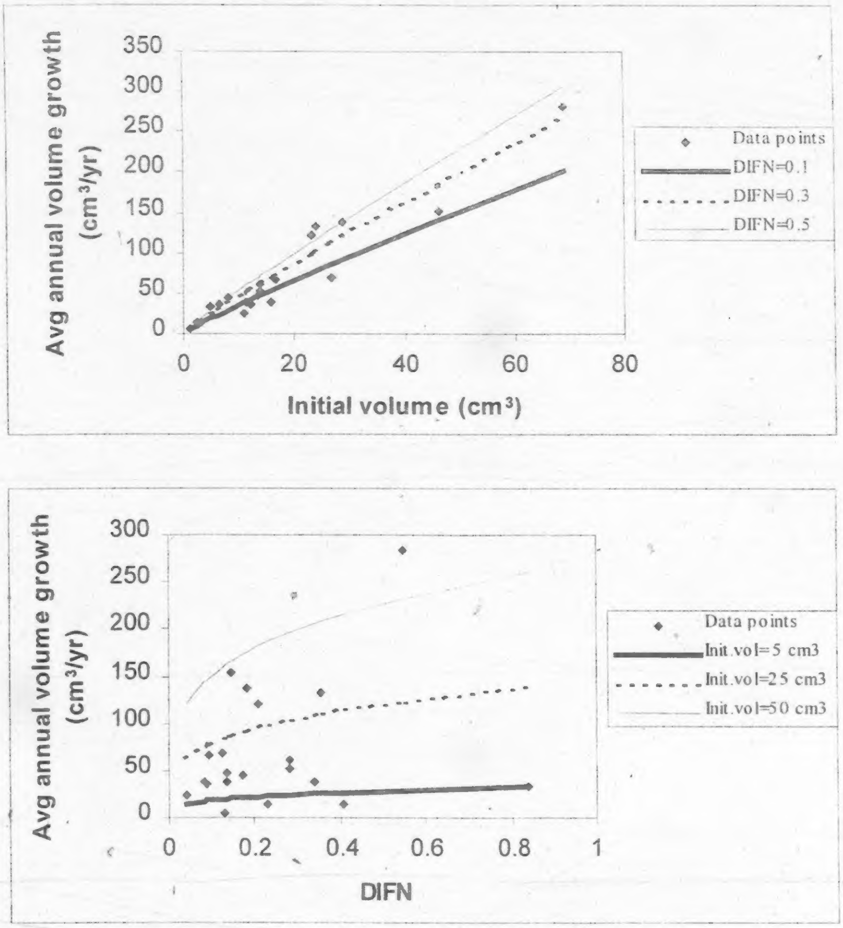


Figure 3.11. Scatterplot showing the relationship between average annual stem volume growth and transmittance at the tree crown and tree volume at the beginning of the measurement period. The lines are described by the equation: Ln(Vol growth)= 2.042 + 0.259*Ln(DIFN) + 0.911*Ln(Init.vol); R^2=0.940; RMSE=0.246; n=20.

3.4 Discussion

The response of white spruce to increased availability of light depends upon the degree and timing of the increased light levels and the growth variable under consideration. If gaps are formed in the late spring or early summer in a mixedwood stand, white spruce will go through a period of stress from the sudden increase in light levels but it generally acclimates within a short time as its needle development in the spring was under relatively high light levels which may have allowed development of characteristics more like sun leaves (Man and Lieffers 1997).

With its moderate shade tolerance, white spruce tends to be plastic in its response to a change in available light and adapts its physiology and morphology to take advantage of increased light. Height growth of spruce is often very similar in high and low light conditions (Coates et al. 1994; Lieffers and Stadt 1994; Jobidon 2000) whereas diameter growth is more positively correlated with an increase in light availability (Coates et al. 1994; Pacala et al. 1994; Wright et al. 1998; Jobidon 2000). This result is somewhat different from what was found in this study where height growth increased with increasing light although the R^2 values were only 0.24 and 0.20 for Siphon Creek and Slave Lake respectively (Table 3.6). Radial growth generally increased with increasing light in this study as well but the R^2 value was substantially larger for the Siphon Creek spruce (0.42) compared to the Slave Lake spruce (0.16)

Increasing diameter growth has been linked by several studies with increases in available light level (Wright et al. 1998; Coates and Burton 1999; Groot 1999). Many authors have also found that the response of a sapling to increased light is dependent on the initial size of the tree (Hatch et al. 1975; Cole and Lorimer 1994; Biging and Dobbertin 1995; Choi et al. 2001; Claveau et al. 2002;Webster and Lorimer 2003). This study agrees with these general findings and the best relationship was found between stem volume growth and transmittance and initial crown surface area. The growth potential of saplings with larger crown surface area and leaf area should be superior to those with very little crown surface area for trees growing in similar light environments.

The stem volume growth of trees near Siphon Creek and near Slave Lake can be best described by a relationship that involves both the crown surface area at the beginning of the growth period and the amount of light that is available for use at the crown surface. The relative effect of the two independent variables is different though between these two locations. These differences could be the result of the overall smaller size of trees near Slave Lake or some of these differences may also result from differing stand development experienced in these two locations. The spruce near Siphon Creek have been part of an ongoing research trial that had light levels manipulated through thinning and cleaning treatments starting within 2 years or less after planting and this may have caused a different growth response than the spruce near Slave Lake which had received no specific treatment but were exposed to different light regimes based on natural crown closure and gap creation resulting from self-thinning.

Results indicate that regression models for describing volume growth differ between spruce sampled at Slave Lake and Siphon Creek. However, because of the difference in the size of the white spruce trees near Siphon Creek and near Slave Lake, the differences in their respective stem volume growth rates should only be compared where they have overlap in initial tree size. This occurs for crown surface area values around 15,000 cm^2. At low light levels, growth rates for spruce near Siphon Creek are greater than those near Slave Lake but not by a large amount. For high light levels, growth rates are more than two times greater for trees near Siphon Creek as for trees that have equal crown surface areas near Slave Lake. These differences may result from climatic and other factors that influence site growth. However, they may also be because of the early treatment of spruce at Siphon Creek creating better overall conditions. Jobidon (2000) found that previous competition status affects future growth rates and Wood and vonAlthen (1993) found increased growth response with herbicide treatment carried out closer to plantation establishment for white and black spruce in boreal Ontario.

Trees generally have better response to release from competition when they are young because of increased plasticity (Richardson et al. 2000). Release of white spruce from aspen competition improved both diameter and height growth of spruce more in young stands than in intermediate-aged stands, but release of spruce at a very young age runs the risk of them being outgrown and overtopped by aspen sucker regrowth (Yang 1989). Yang (1989) recommends that spruce should be at least 3.5 m in height or 25-30 years of age at release to prevent aspen sprouts and other underbrush competition.

Yang (1989) found that the response in spruce height growth to release from aspen competition was greatest in 2 to 6 meter tall stems. Claveau et al. (2002) suggests that the effect of increasing growth rates with increasing age (height) begins to diminish as the spruce reach 5 to 6 meters in height and that maximum growth rates occur when optimum crown volumes are reached which typically happens when conifers are 5 to 6 meters tall.

Lees (1966) found that removal of competing aspen within twice the crown width of spruce crop trees resulted in a marked increase in both height and diameter growth of spruce and control of suckering by cut stump poisoning prevented suckering and sprouting of the aspen for several years. Peterson and Peterson (1995) recommend removal of aspen in a sufficient diameter to allow normal spruce crown development and found that the greatest growth responses come from 20 to 40 year old stands. They suggest that to stay ahead of new aspen sucker growth and shrub competition, understory white spruce should be at least 2.5 m tall. Stands with spruce less than this height would likely require more than one treatment.

The amount of light absorbed by a tree should influence the growth rate of that tree but it appears that for young white spruce growing beneath an aspen overstory that the relationship is not a simple one. There is a strong relationship between the leaf area of a tree and its more easily estimated crown surface area. The relationship between the absorbance of a tree in the open and its leaf area was significant but not as strong as expected. This may be because of measurement difficulties or it may be because of the small sample size used in this study. Also the calculation of DIFN using the LAI-2000 assumes random distribution and orientation of foliage. The effect of violation of this assumption may be too great for this use.

Canopy absorbance on its own predicts both height and root collar diameter growth with moderate R^2 values but poorly estimates stem volume growth. Many of the 20 trees in this study were suppressed and this would often be the case in mixedwood stands. The poor relationship found between stem volume growth and canopy absorbance may be partially explained by the suppressed status of the white spruce as was found by Brunner and Nigh (2000) for suppressed trees.

Stem volume growth is well predicted by initial stem volume and the addition of canopy absorbance to the model improves the predictive ability from an R^2 value of 0.9 to 0.95. A very similar amount of variation in a model that predicts stem volume growth can be explained by the substitution of DIFN at the tree surface for canopy absorbance. These measurements are perhaps more readily attainable than canopy absorbance.

3.5 Conclusions

Provision of increased light availability for white spruce growing beneath an aspen canopy will improve the stem volume growth of the spruce provided that the spruce has developed sufficiently to be able to survive the increased light levels and is large enough to stay ahead of the re-sprouting aspen. More vigourous spruce with more crown surface area will respond the most regardless of the light level. The best growth response will be realized when spruce have high crown surface areas and high light levels.

The amount of leaf area carried by young white spruce saplings is related to how much light an individual tree can absorb but for suppressed trees a simple relationship was not found between stem volume growth and the amount of light a tree absorbs in the canopy. Stem volume growth is best predicted by initial tree size and the addition of canopy absorbance is only of marginal benefit.

The differences in growth rates between spruce at Siphon Creek and near Slave Lake suggest that early treatment to increase light levels may produce increases in growth rates that compound over time. This suggests that early treatment may be worthwhile even knowing that more treatments will likely be required before the white spruce can maintain a competitive advantage over the aspen re-sprouting.

Results from this study emphasize the importance of regional development of models relating volume growth of small spruce to light levels and crown size. This need likely arises because of the effects of site factors and physiology on growth rates. Further study is required to evaluate alternative approaches for developing generally applicable models.

3.6 References

Aphalo, P.J., and Ballaré, C.L. 1995. On the importance of information-acquiring system in plant-plant interactions. Funct. Ecol. 9: 5-14.

Awada, T., and Redmann, R.E. 2000. Acclimation to light in planted and naturally regenerated population of white spruce seedlings. Can. J. Bot. Vol. 78: 1495-1504.

Beaudry, L., Coupé, R., Delong, C., & Pojar, J. 1999. Plant indicator guide for Northern British Columbia : boreal, sub-boreal, and subalpine biogeoclimatic zones. Land Management Handbook #46. B.C. Min. of For. Res. Branch.

Beckingham, J.D., and Archibald, J.H. 1996. Field guide to ecosites of northern Alberta. Can. For. Ser. Special Report 5. 412 pp.

Biging, G.S., and Dobbertin, M. 1995. Evaluation of competition indices in individual tree growth models. Forest Science. 41: 360-377.

Brace, L.G., & Bella, I. E. 1988. Understanding the understory: dilemma and opportunity. In Aspen Symposium '89. Proc. Symp. July 25-27, 1989. Duluth, Minn. R.D. Adams (editor). U.S.D.A. For. Serv. North Cent. For. Exp. Sta., St. Paul, Minn. Gen. Tech. Rep. NC-140. pp 69-86.

Brand, D.G. 1991. The establishment of boreal and sub-boreal conifer plantations: an integrated analysis of environmental conditions and seedling growth. Forest Science 37(1) : 68-100.

Brunner, A., and Nigh, G. 2000. Light absorption and bole volume growth of individual Douglas-fir trees. Tree Physiology 20: 323-332.

Cannell, M.G.R., and Grace, J. 1993. Competition for light: detection, measurement and quantification. Can. J. For. Res. 23: 1969-1979.

Carlson, D.W., and Groot, A. 1997. Microclimate of clear-cut, forest interiors, and small openings in trembling aspen forest. Agric. For. Meterology. 87: 313-329.

Chen, H,Y.H. 1997. Interspecific responses of planted seedlings to light availability in interior British Columbia: survival, growth, allometric patterns, and specific leaf area. Can. J. For. Res. 27: 1383-1393.

Choi, J., Lorimer,C.G., Vanderwerker, J., Cole, W.G., and Martin, G.L. 2001. A crown model for simulating long-term stand and gap dynamics in northern hardwood forests. For. Ecol. Man. 152: 235-258.

Claveau, Y., Messier, C., Comeau, P.G., and Coates, K.D. 2002. Growth and crown morphological responses of boreal conifer seedlings and sapling with contrasting shade tolerance to a gradient and light and height. Can. J. For. Res. 32: 458-468.

Coates, K.D., Haeussler, S., Lindeburgh, S., Pojar, R., and Stock, A.J. 1994. Ecology and silviculture of interior spruce in British Columbia. B.C. Ministry of Forests. FRDA Report 220 182 pp.

Coates, K.D., and Burton, P.J. 1999. Growth of planted tree seedlings in response to ambient light levels in northwestern interior cedar-hemlock forests of British Columbia. Can. J. For. Res. 29: 1374-1382.

Cole, W.G., and Lorimer, C.G. 1994. Predicting tree growth from crown variables in managed northern hardwood stands. For. Ecol. Man. 67:159-175.

Comeau, P.G., Braumandl, T.F., and Xie, C. 1993. Effects of overtopping vegetation on light availability and growth of Englemann spruce (*Picea engelmannii*) seedlings. Can. J. For. Res. 23: 2044-2048.

Comeau, P.G., Gendron, F., and Letchford, T. 1998. A comparison of several methods for estimating light under a paper birch mixedwood stand. Can. J. For. Res. 28: 1843-1850.

Coopersmith, D., and Hall, E. 1999. The Siphon Creek mixedwood trial: the use of a simple height-to-diameter ratio to predict the growth success of planted white spruce seedlings beneath aspen canopies. B.C. Ministry of Forests Research Note PG-17 EP 1077. 10 pp.

Crossley, D.I. 1976. Growth response of spruce and fir to release from suppression. For. Chron. 189-193.

Daniel, T.W., Helms, J.A., & Baker, F.S. 1979. Principle of silviculture. McGraw-Hill. New York. 500 pp.

David, A.J., Zasada, J.C., Gilmore, D.W., and Landhäusser, S.M. 2001. Current trends in the management of aspen and mixed aspen forests for sustainable production. For. Chron. 77(3): 525-532.

Duchesneau, R., Lesage, I., Messier, C., and Morin, H. 2000. Effects of light and intraspecific competition on growth and crown morphology of two size classes of understory balsam fir saplings. For. Ecol. Man. 5071: 1-11.

Gendron, F.,Messier, C., and Comeau, P.G. 1998. Comparison of different methods for estimating light transmittance in forests. Agric. For. Met. 92: 55-70.

Givnish, T.J. 1988. Adaptation to sun and shade: a whole-plant perspective. Aust. J. Plant Physiol. 15: 63-92.

Greene, D.F., Zasada, J. C., Sirois, L., Kneeshaw, D., Morin, H., Charron, I., and Simard, M.-J. 1999. A review of the regeneration dynamics or North American boreal forest species. Can. J. For. Res. 29: 824-839.

Greene, D.F., Kneeshaw, D.D., Messier, C.,Lieffers, V., Cormier, D. Doucet, R., Coates, K.D., Groot, A., Grover, G., and Calogeropoulos, C. 2002. Modelling silvicultural alternatives for conifer regeneration in boreal mixedwood stands (aspen/white spruce/balsam fir). For. Chron. 67(2): 281-295.

Groot, A. 1999. Effects of shelter and competition on the early growth of planted white spruce (*Picea glauca*). Can. J. For. Res. 29: 1002-1014.

Grossnickle, S.C. 2000. Ecolphysiology of northern spruce species. The performance of planted seedlings. NRC Research Press. Ottawa. pp. 54-172.

Hatch, C.R., Gerrald, D.J., and Tappeiner, J.C. II. 1975. Exposed crown surface area: a mathematical index of individual tree growth potential. Can. J. For. Res. 5:: 224-228.

Jobidon, R. 2000. Density-dependent effects of northern hardwood competition on selected environmental resources and young white spruce (*Picea glauca*) plantation growth, mineral nutrition, and stand structural development – a 5-year study. For. Ecol. Manage. 130:77-97.

Kneeshaw, D.D., Williams,H., Nikinmaa, E., and Messier, C. 2002. Patterns of above- and below-ground response of understory conifer release 6 years after partial cutting. Can. J. For. Res. 32: 255-265.

Kobe, R.A., and Coates, K.D. 1997. Models of sapling mortality as a function of growth to characterize interspecific variation in shade tolerance of eight tree species of northwestern British Columbia. Can. J. For. Res. 27: 227-236.

Lamontagne, M. , Margolis, H., and Bigras, F. 1998. Photosynthesis of black spruce, jack pine, and trembling aspen after artificially induced frost during the growing season. Can. J. For. Res. 28: 1-12.

Lees, J.C. 1966. Release of white spruce from aspen competition in Alberta's spruce aspen forest. Gov't of Canada, Ent of Forestry Publication No. 1163.

Lieffers, V.J., and Stadt, K.J. 1994. Growth of understory *Picea glauca, Calamagrostis canadensis* and *Epilobium augustifolium* in relation to overstory light transmission. Can. J. For. Res. 24: 1193-1198.

Lieffers, V.J., Mugasha, A.G., and MacDonald, S.E. 1993. Ecophysiology of shade needles of *Picea glauca* saplings in relation to removal of competing hardwoods and degree of prior shading. Tree Physiol. 12: 271-280.

Lieffers, V.J., Pinno, B.D., and Stadt, K.J. 2002. Light dynamics and free-to-grow standards in aspen-dominated mixedwood forests. For. Chron. 78(1): 137-145.

Logan, K.T. 1969. Growth of tree seedlings as affected by light intensity: IV. Black spruce, white spruce, balsam fir, and eastern white cedar. Canadian Forestry Service. Ottawa. Publication 1256.

MacDonald, G.B. 1996. Silviculture of temperate & boreal broadleaf conifer mixtures. Land Management Handbook #36. BC Ministry of Forests- Research Branch. pp 102-113.

MacFarlane, D.W., Green, E.J., Brunner, A., and Burkhart, H.E. 2002. Predicting survival and growth rates for individual loblolly pine trees from light capture estimates. Can. J. For. Res. 32: 1970-1983.

Man, R., and Lieffers, V.J. 1997. Seasonal photosynthetic responses to light and temperature in white spruce (*Picea glauca*) seedlings planted under an aspen (*Populus tremuloides*) canopy and in the open. Tree Physiol. 17: 437-444.

McCarthy, J. 2001. Gap dynamics of forest trees: a review with particular attention to boreal forests. Environ. Rev. 9: 1-59.

Messier, C., Doucet, R., Ruel, J. Claveau, Y., Kelly, C., and Lechowicz, M.J. 1999. Functional ecology of advance regen\eration in relation to light in boreal forests. Can. J. For. Res. 29: 812-823.

Navratil, S. 1996. Silviculture of temperate & boreal broadleaf conifer mixtures. Land Management Handbook #36. BC Ministry of Forests- Research Branch. pp 35-46.

Oliver, C.D., and Larson, B.C. 1996. Forest stand dynamics. Update edition John Wiley & Sons, Inc. New York. pp. 9-88.

Ott, P. 1997. The use of indicator variables in non-linear regression. B.C. Ministry of Forests, Victoria, B.C. Biometrics Information Pamphlet No. 56.

Pacala, S.W., Canham, C.D., and Silander, J.A. Jr. 1993. Forest models defined by field measurements: I. the design of a northeastern forest simulator. Can. J. For. Res. 23: 1980-1988.

Pacala, S.W., Canham, C.D., Silander, J.A. Jr., and Kobe, R.K. 1994. Sapling growth as a function of resources in a north temperate forest. Can. J. For. Res. 24: 2172-2183.

Pacala, S.W., Canham, C.D., Saponara, J., Kobe, R.K., and Ribbens, E. 1996. Forest models defined by field measurements: estimation, error analysis and dynamics. Ecol. Monogr. 66(1): 1-43.

Peterson, E.B., and Peterson, N.M. 1995. Aspen managers' handbook for British Columbia. Canada-British Columbia Partnership Agreement on Forest Resource Development. FRDA II. FRDA Report 230. Victoria, BC, Canada.

Ramsey, F.L., and Schafer, D.W. 1997. The statistical sleuth – a course in the methods of data analysis. Duxbury Press Belmont Ca. 742 pp.

Richardson, A.D., Berlyn, G.P., Ashton, P.M.S., Thadani, R., Cameron, I.R. 2000. Foliar plasticity of hybrid spruce in relation to crown position and stand age. Can. J. Bot. 78: 305-317.

Rowe, J.S. 1972. Forest regions of Canada. Canadian Forestry Service. Publication No. 1300.

Ruel, J-C., Messier, C., Doucet, R., Claveau, Y., and Comeau, P. 2000. Morphological indicators of growth response of coniferous advance regeneration to overstory removal in the boreal forest. For. Chron. 76(4): 633-642.

Spittlehouse, D.L., and Stathers, R.J. 1990. Seedling Microclimate. Land Management Report #65 BC Ministry of Forests.

Sprugel, D.R., Brooks, J.R., and Hinckley, T.M. 1996. Effects of light on shoot geometry and needle *Abies amabilis*. Tree Physiol. 16: 91-98.

Thorpe, J.P. 1992. The ecology and silviculture of mixed-species forests. Kluwer Academic Publishers. Netherlands 287 pp.

Wang, J.R., Letchford, T., Comeau, P.G., Coppersmith, D. 2000. Foliar responses of understory *Abies lasiocarpa* of different degrees of release cutting in a *Betula papyrifera* and conifer mixed species stand. Scand. J. For. Res. 15: 611-620.

Webster, C.R., and Lorimer, C.G. 2003. Comparative growing space efficiency of four tree species in mixed conifer-hardwood forest. For. Ecol. Man. 177: 361-377.

Wood, J.E., and von Althen, F.W. 1993. Establishment of white spruce and black space in boreal Ontario: effects of chemical site preparation and post planting weevil control. For. Chron. 69: 554-560.

Wright, E.F., Coates, K.D., Canham, C.D., and Bartemucci, P. 1998. Species variability in growth response to light across climatic regions in northwestern British Columbia. Can. J. For. Res. 28: 871-886.

Wright, E.F., Canham, C.D., and Coates, K.D. 2000. Effects of suppression and release on sapling growth of 11 tree species of northern, interior British Columbia. Can. J. For. Res. 30: 1571-1580.

Yang, R.C. 1989. Growth response of white spruce to release from trembling aspen. Information Report NOR-X-302 Northern Forestry Centre 24 pp.

4. Implications of tending individual white spruce using radial treatments

4.1 Introduction

Management practices that emulate natural processes have become more prevalent in recent years. Mixedwood stands progress through a natural process whereby trembling aspen and white spruce often become established together on a site following a natural or anthropogenic disturbance (Kelty et al.1992; Thorpe 1992). Aspen with its superior juvenile growth, generally dominates in the first 15 to 25 years with white spruce surviving and growing slowly in its understory position (Peterson and Peterson 1995; David et al. 2001; Lieffers et al. 2002). At this point, the stand begins to self-thin, gaps are formed and with increased light the spruce begins to grow more vigourously (Lieffers et al. 2002).

In order to meet a management objective of promoting the growth and vigour of white spruce while at the same time maintaining a vigourous aspen component, the competition for light that young spruce experience needs to be decreased at an earlier age. This objective can be met by giving spruce a head start in a mixedwood stand prior to harvest via practices that include underplanting, advanced regeneration protection, seed bed and seed source management prior to harvest as well as utilization of partial or strip cutting techniques (Brace and Bella 1988; MacDonald 1996; Navratil 1996; Carlson and Groot 1997; Greene et al. 1999;David et al. 2001; Greene et al. 2002). After harvest, spruce growth can be encouraged by thinning or by creating circular gaps around young spruce trees. Lees (1966) found significant increases in both height and diameter growth of white spruce with removal of aspen within twice the crown width of a spruce crop tree. Large canopy gaps on the other hand can lead to increased incidence of radiative frost events during the growing season as was also experienced by larger white spruce under an aspen canopy in Ontario (Groot and Carlson 1996).

4.2 Effects of treatment radius on spruce growth

Results presented in chapter 2 show that post-treatment transmittance at the center of a circular opening 1 meter above the ground can be predicted by sky view factor (SVF) and pre-treatment transmittance levels. Sky view factor is calculated as:

$$\mathbf{SVF = \cos^2 (\tan^{-1}(2H/D))}$$

where H is the forest height and D is the diameter of the circular opening (Oke 1987).

Stands from 2 to 8 meters in height and from locations near Fort St.John and near Slave Lake can all utilize a common model (Equation 1).

$$\mathbf{1)\ Ln(SVF) = \frac{-0.2998 + Ln(Post\ treatment\ DIFN) - 0.3810Ln(Pre\ treatment\ DIFN)}{0.2312}}$$

Where SVF=sky view factor; Post treatment DIFN = diffuse non-interceptance after circular opening implementation and Pre treatment DIFN is the pre-treatment transmittance

Based on this equation, if you have a stand with a pre-treatment transmittance level of 0.1 you will need an opening with a SVF of 0.61 to achieve a post-treatment transmittance level of 0.5, whereas if pre-treatment transmittance is 0.2 you would only need an opening with a SVF of 0.19 to achieve this same post-treatment transmittance level. To achieve a SVF of 0.61 in an 8 meter tall stand, an opening 20 meters in diameter would be required while a 3 meter tall stand would require a 7.5 meter diameter opening. A SVF of 0.19 in an 8 meter tall stand requires an opening of 7.8 meters in diameter and a 3 meter tall stand requires an opening diameter of 2.9 meters.

SVF will change through time for a given diameter of opening because of differing height growth rates for trembling aspen and white spruce. Site Tools (B.C. Ministry of Forests 2000) can be used to predict expected height growth trends of young aspen and spruce (Table 4.1) and using these height growth curves, the change in SVF over time for a given diameter of opening can be determined (Figure 4.1). Use of these height growth trends assumes that young aspen stands are dense and that spruce is relatively open grown (ie they are growing in height at a rate that is close to site potential). The assumption should be realistic for aspen and spruce but the estimates of overall SVF may be slightly optimistic. There is also an assumption that any lateral growth of aspen into a created opening will be consistent to maintain consistent circular views. Based on this relationship, if a 4 meter diameter opening were made in a 5 year old stand a SVF of 0.66 would be created at the top of a spruce tree in the center of the opening but with aspens' earlier growth advantage the SVF would decrease to 0.18 by 13 years.

Table 4.1. Table of height by breast height age and site index for trembling aspen[1] and white spruce[2]

Age at breast height	Aspen Site Index (50)=21m	Spruce Site Index (50)=17m
	Height (m)	
0	1.30	1.30
5	3.21	2.14
10	5.73	3.54
15	8.27	5.19
20	10.67	6.96
25	12.88	8.76
30	14.88	10.55
35	16.67	12.28
40	18.28	13.94
Years to breast height	3.17	14.67

[1] Alberta Forest Service (1985) site index equation; [2] Goudie (1984) (natural) site index equation

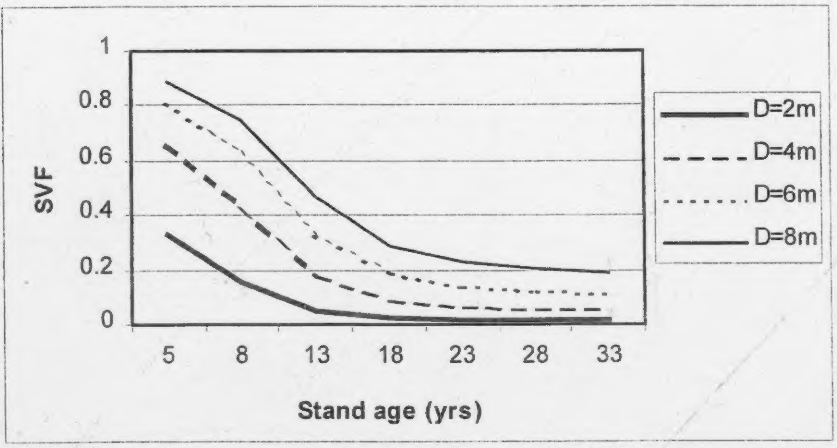


Figure 4.1. Representation of how SVF at the top of the spruce will change over time ~~using~~ expected height growth trends from SITE-Tools (SI50 of 17m for spruce and 21m for aspen). D=opening diameter in meters.

Vertical light profiles presented in chapter 2 can also be utilized in conjunction with the trends illustrated in Figure 4.1 to examine the change in transmittance levels over time for various opening diameters. Two separate equations (from chapter 2) for 3.5-8 meter tall stands near Fort St. John (FSJ) and Slave Lake (SL) can be applied (Equation 2 and 3)

2) FSJ $\text{Ln(extinction)} = -3.1114 - 0.115\text{Ln(RelativeHt)} - 0.2805\text{Ln(SVF)}$

3) SL $\text{Ln(extinction)} = -1.6739 - 0.2741\text{Ln(RelativeHt)} - 0.2084\text{Ln(SVF)}$

Where extinction is 1–transmittance; RelativeHt=height of spruce/height of aspen and SVF would be calculated based on SVF at the top of the spruce within the gap.

Figures 4.2 and 4.3 show how transmittance declines until age 18 and then, because of increasing spruce height growth, relative height of spruce begins increasing and transmittance levels begin to climb. A similar trend is shown for both Fort St. John and Slave Lake but there is a slower recovery in transmittance levels for spruce near Slave Lake.

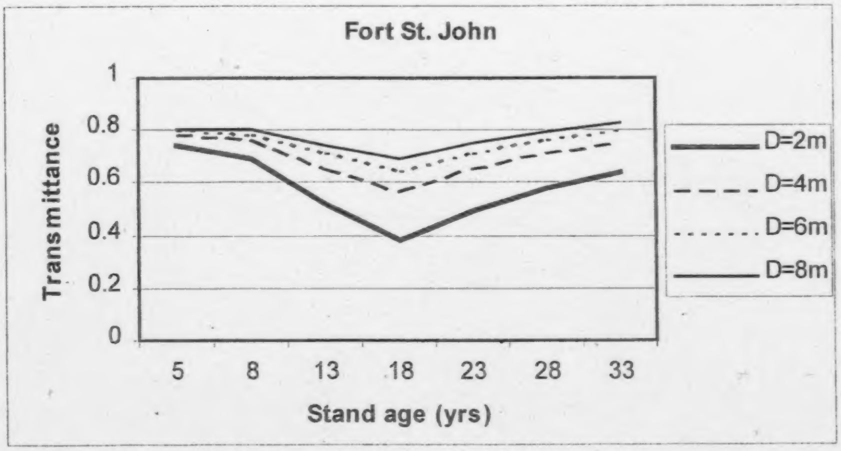


Figure 4.2. Change in transmittance values over time based on expected height growth of aspen and spruce growing within various sized openings utilizing changing SVF at the top of the spruce over time (Figure 4.1) and the vertical light profile relationship described in equation 2. D=opening diameter.

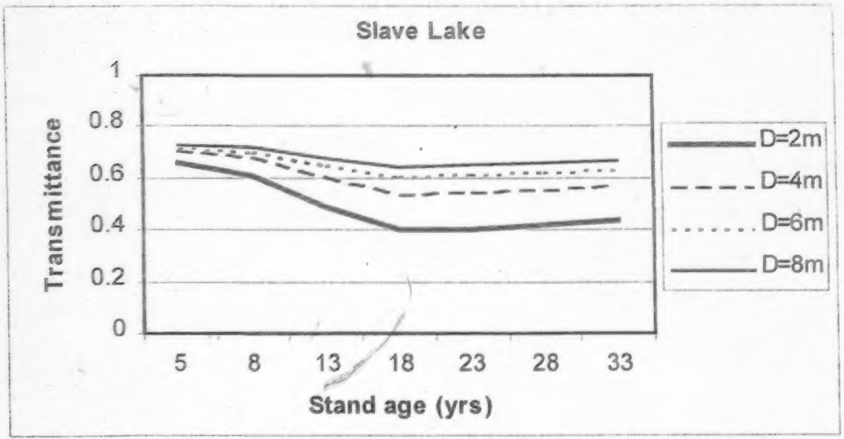


Figure 4.3. Change in transmittance values over time based on expected height growth of aspen and spruce growing within various sized openings utilizing changing SVF at the top of the spruce over time (Figure 4.1) and the vertical light profile relationship described in equation 3. D=opening diameter.

Larger openings can lead to higher incidence of frost especially on calm, clear nights during the growing season (Groot and Carlson 1996; Langvall and Örlander 2001; Langvall and Löfvenius 2002). Even though the temperatures during the 2002 growing season were relatively moderate, some cold temperatures trends are noteworthy. In stands less than 8 meters tall near Slave Lake, for periods during which overnight temperatures are particularly cold, larger SVFs result in lower overnight temperatures at 1 meter above the ground. The variation in minimum seasonal temperature for temperature probes located 1 meter above ground level increases with SVF.

The number of occurrences of temperatures less than -2°C is poorly related to SVF but much higher correlations were found with both the density and height of the stand in which openings were created for probes at both 20 cm and 1 meter above ground level. In created openings there is a increased likelihood of damaging growing season frost at both 20 cm and 1 meter above the ground within shorter, less dense stands. For probes located at 20 cm above ground, particularly at the beginning of the growing season, the accumulated growing degree days increase with increasing SVF. The effect of the size of opening on the likelihood of radiative frost damage is influenced by the height and density of the surrounding stand. Therefore, if treatment is planned in a stand that is short or with patchy stocking, there is an increased chance of frost regardless of opening size. These results suggest that removing aspen around selected individual spruce would be best applied to stands that are well stocked and have good canopy closure. Creating openings that provide a SVF of 0.3 or less as suggested by Groot and Carlson (1996) and as indicated by the small number of points in this study, may be desirable to minimize the number of occurrences of frost and chances of growing season frost injury.

As shown in chapter 3, height, radial and stem volume growth rates of white spruce all increase with increasing light availability. Crown surface area at the beginning of the growth period was found to be significant as an independent variable for describing variation in spruce growth. Because of resulting acceleration in whole tree growth, and crown development, early tending to provide increases in light is likely to provide the greatest overall benefit. The benefits of early treatment to reduce competition have been demonstrated in other studies (Wood and vonAlthen 1993; Richardson et al. 2000). Since treating small spruce trees will likely result in a need for retreatment to control aspen resprouts, Yang (1989) recommends that spruce should be at least 3.5 meters in height before release to allow them to stay ahead of resprouting aspen. Creating small openings with a radius less than the height of the surrounding aspen in a 5-year old mixedwood plantation (ie with a SVF of 0.2 or less), resulted in substantial reductions in vigour of resprouting aspen (P. Comeau pers. comm. 2003), indicating that the need to retreat to control sprouts may be minimized with removal of broadleaf competitors within a small radius. This low vigour may be partially explained by low red/far-red ratios in these openings that have been shown to reduce leaf weight when compared to larger openings with higher red light compositions (FitzGerald and Hoddinott 1983). Treatment radius may need to be enlarged at later ages however, if the objective is to maintain the treated spruce at higher light levels.

The relationship between post-treatment transmittance and SVF and pre-treatment light levels for openings created in 2-8 meter mixedwood stands near Slave Lake and Fort St. John (Figure 2.10) can be combined with the relationships between stem volume growth and initial CSA and DIFN (Figures 3.4 and 3.5) obtained for white spruce at Slave Lake and Siphon Creek. This combined relationship could be used to predict growth given the remaining 3 variables.

From a management perspective (for white spruce growing underneath aspen near Slave Lake), creation of an opening to yield a SVF of 0.5 in a stand with a pre-treatment transmittance level of 0.2 would result in stem volume growth of 66 cm^3/yr when initial spruce CSA is 10,000 cm^2. This same SVF in this stand for a spruce with an initial CSA of 5,000 cm^2 would have a growth rate of 32 cm^3/yr (Equation 4; Figure 4.4).

Slave Lake

Substitution of the post-treatment transmittance relationship (Equation 1) into the growth equation (Figure 3.4) gives:

$$\text{Ln(stem vol growth)} = -5.19 + 1.04\text{Ln(CSA)} + 0.464[0.2998 + 0.2312\text{Ln(SVF)} + 0.381\text{Ln(Pre-trt trans.)}]$$

which can be rearranged to yield equation 4.

4) Ln(stem vol growth) = – 5.05 + 1.04Ln(CSA) +).107Ln(SVF) + 0.177Ln(Pre-trt trans.)

Where CSA =crown surface area at the beginning of the measurement period

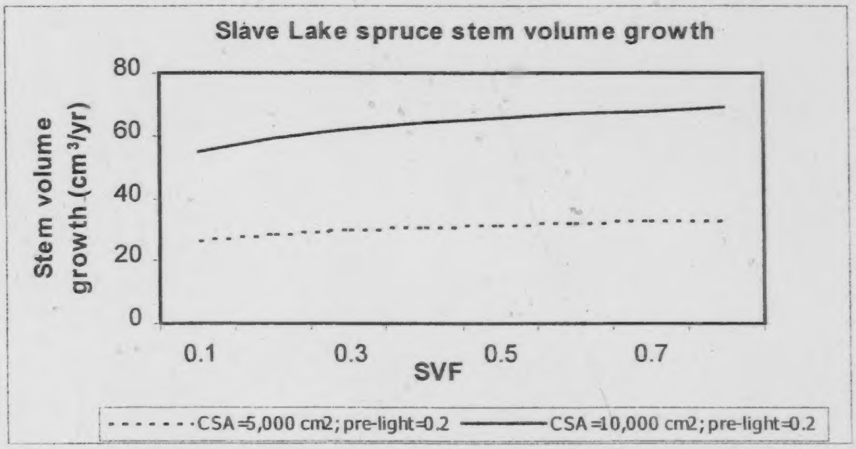


Figure 4.4. Stem volume growth as predicted from equation 4 for white spruce near Slave Lake for trees with initial CSA of 5,000 and 10,000 cm^2 under pre-treatment light levels of 0.2.

For spruce, such as those treated at Siphon Creek, creation of an opening to yield a SVF of 0.5 in a stand with a pre-treatment transmittance level of 0.2 would result in stem volume growth of 541 cm^3/yr when initial spruce CSA is 30,000 cm^2. This same SVF in this stand for a spruce with an initial CSA of 75,000 cm^2 would have a growth rate of 2057 cm^3/yr (Equation 5; Figure 4.5).

Siphon Creek

Substitution of the post-treatment transmittance relationship (Equation 1) into the growth equation (Figure 3.5) gives:

$$\mathrm{Ln(stem\ vol\ growth)} = -8.42 + 1.46\mathrm{Ln(CSA)} + 0.65[0.2998 + 0.2312\mathrm{Ln(SVF)} + 0.381\mathrm{Ln(Pre\text{-}trt\ trans.)}]$$

which can be rearranged to yield equation 5.

5) $$\mathbf{Ln(stem\ vol\ growth)} = -8.23 + 1.46\mathbf{Ln(CSA)} + 0.15\mathbf{Ln(SVF)} + 0.247\mathbf{Ln(Pre\text{-}trt\ trans.)}$$

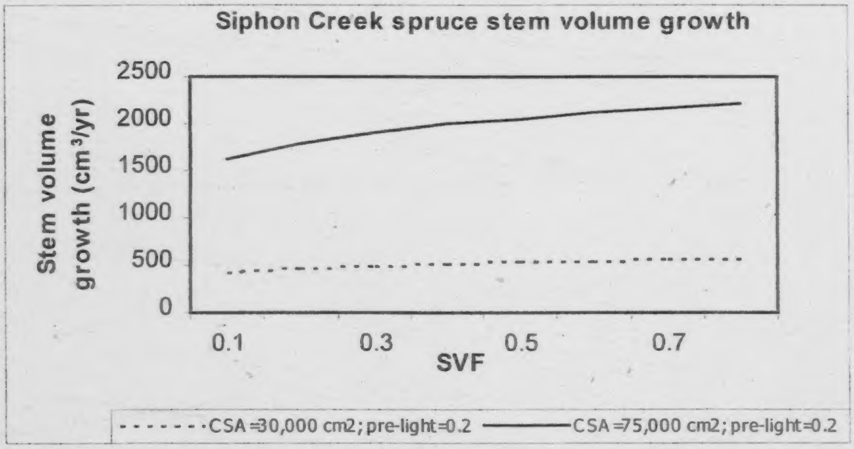


Figure 4.5. Stem volume growth as predicted from equation 4 for white spruce near Slave Lake for trees with initial CSA of 30,000 and 75,000 cm^2 under pre-treatment light levels of 0.2.

Individual tree tending in this manner will accelerate development of codominant and dominant spruce in the stand leading to earlier merchantability and potentially increase volume of spruce at an early rotation. Spruce yield will depend on the number of spruce tended and aspen yield will depend on the number of spruce tended as well as the diameter of the treatment. Treatment of 400 spruce per hectare using a opening size of 4 meter in diameter would lead to 50% of the area being treated. The cost implications for such a treatment in a 5 year old stand would be approximately $400/ha using brush saws or basal bark application of release herbicide. The cost of later treatments would be higher due to larger sizes of treated aspen, although girdling or stem injection with herbicides may be effective and less expensive.

This study has raised a number of issues that will require further study. A trial that looks at the influence of opening size on frost that stratifies stands based on height and density and ensures clipping of all resprouting vegetation adjacent to temperature probes throughout the growing season could better address the temperature question. An in-depth study of the yield implications of tending individual spruce, the need for and timing of retreatment and field testing of this treatment as a silvicultural tool would be beneficial.

4.3 Conclusions

Post-treatment transmittance levels can be predicted by SVF and light levels prior to treatment. A common model can be utilized by 2 –8 meter tall mixedwood stands on mesic, medium nutrient sites near Slave Lake and Fort St. John. Vertical light profiles are different for stands near Fort St. John and near Slave Lake as well as for stands less than 3.3 meters tall. These differences are likely due to differences in crown architecture and distribution of leaf area. Utilizing available height growth curves for aspen and white spruce, results indicated that creating openings with a 4 or 6 meter diameter may be sufficient to provide white spruce with light levels exceeding 40% of open sky values at the top of the tree, over the life of the tree. Creating opening of this size at ages 8 or later is likely to maintain sky view factor below 0.3, and will provide substantial protection from growing season frost if surrounding aspen stands are dense.

4.4 References

B.C. Ministry of Forests. 2000. Site Tools 3.2i. B.C. Ministry of Forests, Research Branch, Victoria, B.C.

Brace, L.G., & Bella, I. E. 1988. Understanding the understory: dilemma and opportunity. In Aspen Symposium '89. Proc. Symp. July 25-27, 1989. Duluth, Minn. R.D. Adams (editor). U.S.D.A. For. Serv. North Cent. For. Exp. Sta., St. Paul, Minn. Gen. Tech. Rep. NC-140. pp 69-86.

Carlson, D.W., and Groot, A. 1997. Microclimate of clear-cut, forest interiors, and small openings in trembling aspen forest. Agric. For. Meterology. 87: 313-329.

Comeau, P.G. 2003. Personal communication.

David, A.J., Zasada, J.C., Gilmore, D.W., and Landhäusser, S.M. 2001. Current trends in the management of aspen and mixed aspen forests for sustainable production. For. Chron. 77(3): 525-532.

FitzGerald, R.D., and Hoddinott, J. 1983. The utilization of carbohydrates in aspen roots following partial or complete top removal. Can. J. For. Res. 13: 685-689.

Greene, D.F., Zasada, J. C., Sirois, L., Kneeshaw, D., Morin, H., Charron, I., and Simard, M.-J. 1999. A review of the regeneration dynamics or North American boreal forest species. Can. J. For. Res. 29: 824-839.

Greene, D.F., Kneeshaw, D.D., Messier, C.,Lieffers, V., Cormier, D. Doucet, R., Coates, K.D., Groot, A., Grover, G., and Calogeropoulos, C. 2002. Modelling silvicultural alternatives for conifer regeneration in boreal mixedwood stands (aspen/white spruce/balsam fir). For. Chron. 67(2): 281-295.

Groot, A., and Carlson, D.W. 1996. Influence of shelter on night temperatures, frost damage, and bud break of white spruce seedlings. Can. J. For. Res. 26: 1531-1538.

Kelty, M.J., Larson, B.C., and Oliver, C.D. 1992. The ecology and silviculture of mixed-species forests. Kluwer Academic Publishers. Netherlands 287 pp.

Langvall, O. and Örlander, G. 2001. Effects of pine shelterwoods on microclimate and frost damage to Norway spruce seedlings. Can. J. For. Res. 31: 155-164.

Langvall, O., and Löfvenius. 2002. Effect of shelterwood density on nocturnal near-ground temperature, frost injury risk and budburst date of Norway spruce. For. Ecol. Mgmt. 168: 149-161.

Lees, J.C. 1966. Release of white spruce from aspen competition in Alberta's spruce aspen forest. Gov't of Canada, Ent of Forestry Publication No. 1163.

Lieffers, V.J., Pinno, B.D., and Stadt, K.J. 2002. Light dynamics and free-to-grow standards in aspen-dominated mixedwood forests. For. Chron. 78(1): 137-145.

MacDonald, G.B. 1996. Silviculture of temperate & boreal broadleaf conifer mixtures. Land Management Handbook #36. BC Ministry of Forests- Research Branch. pp 102-113.

Navratil, S. 1996. Silviculture of temperate & boreal broadleaf conifer mixtures. Land Management Handbook #36. BC Ministry of Forests- Research Branch. pp 35-46.

Oke, T.K. 1987. Boundary layer climates. 2nd ed. Methuen and Co. New York. pp. 339-356.

Peterson, E.B., and Peterson, N.M. 1995. Aspen managers' handbook for British Columbia. Canada-British Columbia Partnership Agreement on Forest Resource Development. FRDA II. FRDA Report 230. Victoria, BC, Canada.

Richardson, A.D., Berlyn, G.P., Ashton, P.M.S., Thadani, R., Cameron, I.R. 2000. Foliar plasticity of hybrid spruce in relation to crown position and stand age. Can. J. Bot. 78: 305-317.

Thorpe, J.P. 1992. The ecology and silviculture of mixed-species forests. Kluwer Academic Publishers. Netherlands 287 pp.

Wood, J.E., and von Althen, F.W. 1993. Establishment of white spruce and black space in boreal Ontario: effects of chemical site preparation and post planting weevil control. For. Chron. 69: 554-560.

Yang, R.C. 1989. Growth response of white spruce to release from trembling aspen. Information Report NOR-X-302 Northern Forestry Centre 24 pp.